Smart Hydroponics: IoT and ML-Driven Sustainable Farming

Final year project report submitted in partial fulfilment of requirement for degree of Bachelors of Science in Electrical Engineering

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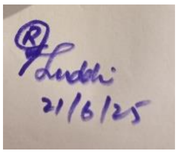
DECLARATION

The project report titled "Smart Hydroponics: IoT and ML-Driven Sustainable Farming" is submitted in partial fulfilment of the degree of Bachelors of Science in Electrical Engineering, to the Department of Electrical Engineering at Namal University, Mianwali.

It is declared that this is an original work done by the team members listed below, under the guidance of our supervisor "Dr. Ahmed Salim". No part of this project and its report is plagiarised from anywhere, and any help taken from previous work is cited properly.

No part of the work reported here is submitted in fulfilment of requirement for any other degree/ qualification in any institute of learning.

Team Members		**Signatures**
Riaz Ud Din	NIM-BSEE-2021-36	
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Dr. Ahmed Salim **Signatures with date** ___________________________

Table of Contents

List of Figures

List of Tables

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Abstract

With the global population projected to reach 9.7 billion by 2050, food demand is expected to increase by 50%. This poses a significant challenge, especially for Pakistan, the fifth most populous country with over 250 million people, where cultivable land is shrinking and water resources are becoming scarce. Conventional agriculture may not meet future demands due to limited arable land and water scarcity. This project presents “Smart Hydroponics: IoT and Machine Learning (ML)-Driven Sustainable Farming System” as a transformative and sustainable solution to address the global challenges of food production, water scarcity and lack of fertile agricultural land. However, traditional vertical farming systems lack real-time monitoring and adaptive control, leading to inefficiencies in resource utilization. Integrating the Internet of Things (IoT) allows continuous monitoring of environmental conditions, while Machine Learning (ML) algorithms can analyze this data to predict optimal growing parameters to optimize resource efficiency, reduce water consumption, and maximize crop yields. This innovative project directly contributes to SDG 2 (Zero Hunger) by enhancing food security, SDG 12 (Responsible Consumption and Production) by reducing resource waste, and SDG 13 (Climate Action) by minimizing carbon footprints associated with traditional farming. Furthermore, the scalability and adaptability of Smart Hydroponics make it a viable solution for urban areas, aligning with SDG 11 (Sustainable Cities and Communities).

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Chapter 1

Introduction

The world's population has steadily grown throughout time, which has a big influence on the food supply. It is predicted that the world's population will rise to 9.7 billion by 2050. Pakistan, with a population of 250 million, is the fifth most populous nation in the world, making the situation even more critical. The amount of land suitable for agriculture is declining as a result of an increase in population and food needs. According to reports, between 1963 and 2009, the amount of land needed for agriculture increased by 42 percent. With an estimated population up to 2050, the globe would need to produce 50 % more food, which will require additional arable land that will simply not be accessible. The amount of arable land per person is predicted to be less than 0.20 ha by 2050, which is less than a third of what it was in 1970 as seen in the figure below [1].

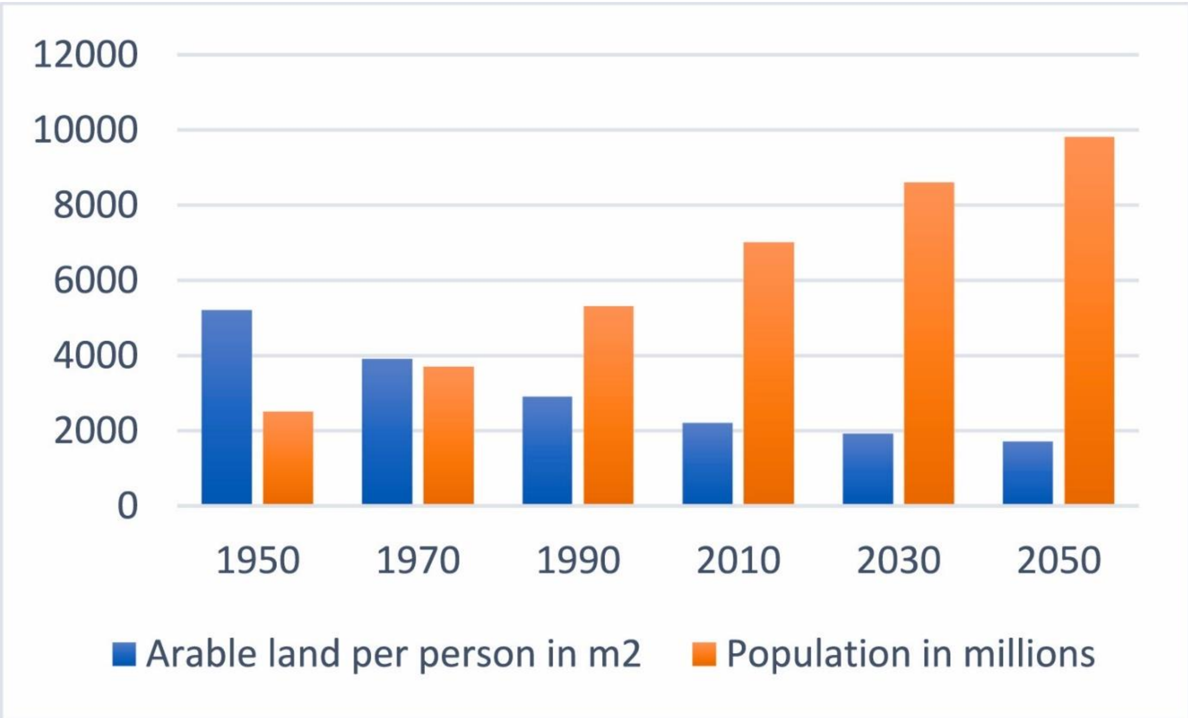


Figure 1: Growing World Population and Declining Agriculture Land.

Consequently, the major issue facing modern society is food production via the traditional agricultural system [2]. As a complementary strategy to address the current scarcity of water and arable land, the vertical farming method is one of the significant alternatives to soil-based agricultural systems [3]. Due to its capacity to conserve water, minimize land use, and support year-round farming, hydroponics, a soilless farming approach, has received a lot of interest. But, traditional hydroponic systems frequently lack adaptive control and real-time monitoring, which results in inefficient use of resources. The use of IoT and ML has created new possibilities for the automation and optimization of hydroponic systems. Real-time data on environmental variables like temperature, humidity, pH, and nutrient levels may be collected via IoT, and ML algorithms can analyze this data to forecast the best growth conditions. The goal of this project is to create an intelligent hydroponic system that combines ML and IoT to produce sustainable and productive agriculture.

Chapter 2

Literature Review

2.1. Overview of Hydroponics

Hydroponics is a method of growing plants without soil, using a nutrient-rich water solution to deliver essential minerals directly to the plant roots. To give the vegetable plants water and nutrients while maintaining adequate support, the plants are planted in a medium like coconut coir and in net cups. Using a hydroponics system for agriculture allows for water conservation because it uses far less water than conventional agricultural methods [4]. A wide variety of fruit and leafy plants may be harvested using hydroponics. Some of them are Tomatoes, peppers, cucumbers, green vegetables, and strawberries [5].

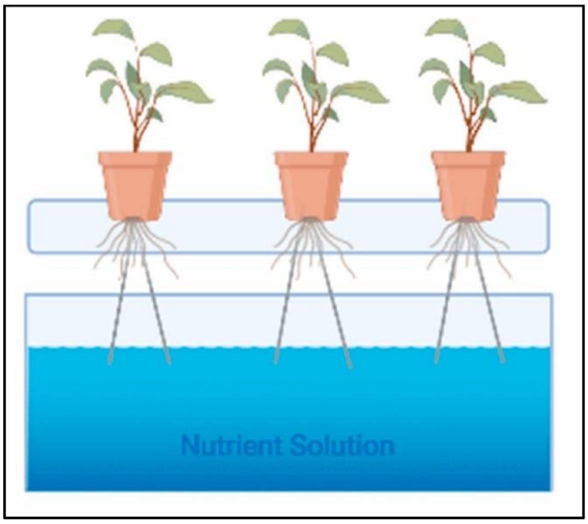


Figure 2: Hydroponics Farming

2.1.1. Types of Hydroponics

There are around 5 different types of hydroponics which are given below:

(a) Wick System

Vegetables are planted directly into rock wool, coco coir, and vermiculite, all of which are absorbing materials. The plants are wrapped with nylon wicks prior to being dipped into the fertilizer solution. The necessary amount of nutrient solution is provided to the plant's roots by capillary action through this nylon wick [1].

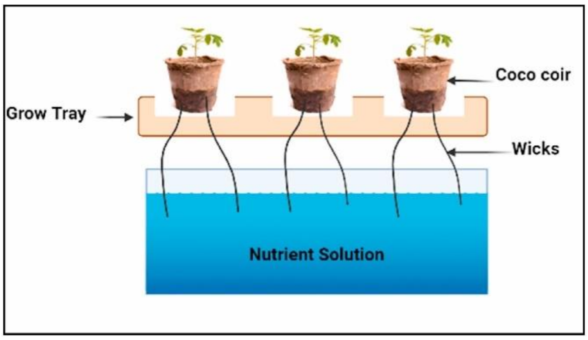


Figure 3: Wick Hydroponics System

(b) Deep Water Culture

This method is often employed for large plants, especially those that yield fruits or vegetables, like tomatoes and cucumbers. The plant's roots are immersed directly into the nutrient tank, allowing for the simple absorption of oxygen and nutrients. Oxygen is delivered directly to the system via an air stone. However, this system is rarely used because of its complexity [6]. The hydroponics bucket system is a well-known example of deep-water culture.

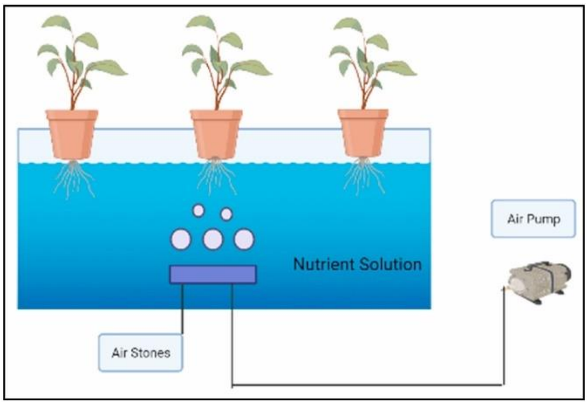


Figure 4: Deep Water Culture Hydroponics System

(c) Ebb and Flow System

In this system, media such rock wool are used to fill plant pots, which serve as both a temporary nutrient solution reservoir and an anchor for roots. A water pump transfers a nutrient solution from the tank to a grow bed until the solution reaches a certain level, at which point it remains in the grow bed for a predetermined period. This hydroponics system may be used to produce a wide range of crops, but it may also have issues such as algae and root rot. This system needs to be improved with filtration methods in order to address these issues [7].

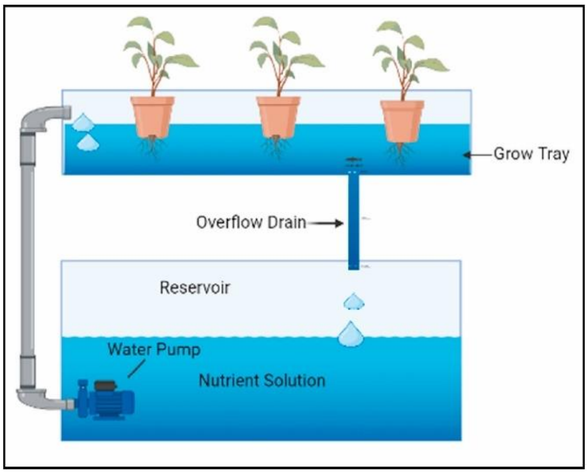


Figure 5: Ebb and Flow Hydroponics System

(d) Nutrient Film Technique

In this system, the nutrient solution is delivered into the grow tray using a motor pump, where it circulates throughout the entire system. The grow tray is designed at an angle, allowing the surplus nutrients to flow back into the tank. The shrub roots are intended to return the mineral-rich solution to the reservoir via a mechanism that has a minimal inclination. However, algae and fungal infections can be a major issue since plants are often submerged in the nutrient tank. The majority of the plants produced commercially using this method are lettuce and other green leafy vegetables [8].

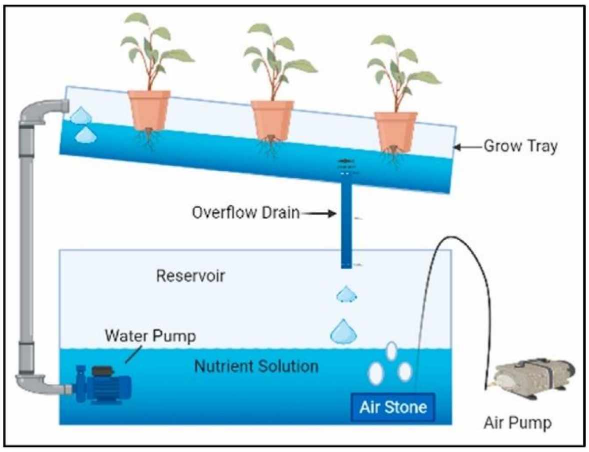


Figure 6: Nutrient Film Technique Hydroponics

(e) Drip System

The drip hydroponics approach is commonly used by both residential and commercial farmers. Nutrient solution is delivered on a set schedule via drippers at the base of each plant's stem in a drip irrigation hydroponics system. The used nutrient solution can be removed from the system or returned to a tank in continuous drip systems. These methods might be recovery- or non-recovery-based [9].

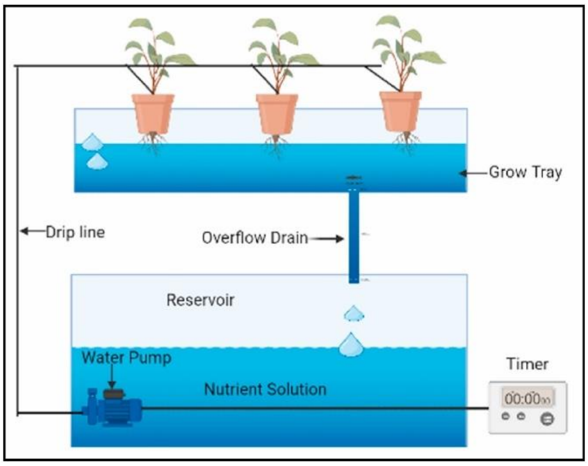


Figure 7: Drip Hydroponics System

2.2. Related Work

Harn Tung Ng, Zhi Kean Tham, Nurul Amani Abdul Rahim at Universiti Sains Malaysia (2023) implemented an IoT-enabled vertical farming system using low-cost embedded microcontrollers (Arduino Nano and NodeMCU ESP8266 Wi-Fi module) and sensors, including DHT22 for temperature and humidity, capacitive soil moisture sensors, and UV LED lights, to monitor and control environmental parameters such as soil moisture, air humidity, and temperature. The system utilized a 12V 4-channel relay module to control water pumps and UV lighting, while an HC4067 multiplexer enabled multiple soil moisture sensors to share a single analog input pin. Data was collected and transmitted to the Blynk cloud via HTTP REST API, and a user interface (UI) was developed using G web development software and hosted on the SystemLink cloud, allowing real-time monitoring and control through any web browser or smart device. The system achieved precise control over irrigation and UV light exposure, with soil moisture levels and environmental conditions displayed numerically and graphically on the UI, updated every 10 seconds [10].

Muhammad E. H. Chowdhury, Amith Khandak, Saba Ahmed and Fatima Al-Khuzaei at Qatar University, Doha Qatar (2020) developed an automated vertical hydroponic system using a Nutrient Film Technique (NFT) structure consisting of 3 shelves with 4 polyvinyl chloride (PVC) pipes per shelf, each containing 9 planting holes, and a 46 L nutrient container made of light-blocking plastic to prevent algae growth. The system incorporated a SUNSUN submersible water pump (600 LPH) for water circulation, LED lights (6K3R4 and K6) for optimal photosynthesis, and a nutrient solution from Fox Farm, along with pH adjustment solutions from General Hydroponics. Sensors such as Atlas Scientific pH and EC sensors, a YF-S201 water flow sensor, a capacitive water level sensor, and temperature and humidity sensors were integrated with an Arduino Mega microcontroller for real-time monitoring and control. The system utilized dosing pumps for nutrient and pH adjustment, an ESP8266 Wi-Fi module for IoT connectivity, and the Thingspeak platform for data visualization and storage. Power consumption was monitored using a custom power meter with ACS712 current and ZMPT101B voltage sensors, while an air conditioning subsystem maintained optimal temperature (19–28 °C). The system achieved efficient plant growth with a monthly water consumption of 8–10 L successfully maintaining stable pH (5.0–7.5) and EC levels. It also featured an SMS alert system for pump failures and demonstrated the ability to grow mint, lettuce, tomato, cucumber, and other plants, offering a cost-effective, scalable, and user-friendly solution for indoor hydroponic farming [11].

Binoy Sasmal, Gobinda Das and Preeti Mallick at national institute of technology arunachal Pradesh, India (2024) developed a vertical farming (VF) system using a combination of IoT sensors, machine learning (ML) algorithms, and advanced agricultural technologies to address challenges in traditional farming. Key components included IoT sensors for monitoring pH, electrical conductivity (EC), light intensity, humidity, temperature, and soil moisture, with data stored and analyzed in the cloud for real-time decision-making. Image recognition techniques, such as Convolutional Neural Networks (CNN) and YOLO (You Only Look Once), were employed for disease detection in crops, using image augmentation methods like rotation, intensity adjustment, and flipping to enhance dataset quality. Ultrasonic sensors were used to measure plant height and optimize light exposure, while robotic navigation systems with linear bearing rods and cameras enabled precise plant monitoring and movement within the VF structure. The system also incorporated artificial lighting using LED lights and LDR sensors to maintain optimal light intensity, and CMOS cameras for tracking plant growth stages. For energy efficiency, renewable energy sources like solar panels and geothermal systems were integrated. The system achieved high accuracy in disease detection (97.71% using CNN) [12].

Rajendiran G and Rethnaraj J at SRM Institute of Science and Technology (2023) developed a hydroponic system using IoT sensors to monitor critical parameters such as pH, electric conductivity (EC), light intensity, humidity, and temperature, integrated with machine learning algorithms like Artificial Neural Networks (ANN), Random Forest (RF), and Support Vector Regression (SVR) for data analysis and yield prediction, achieving an accuracy of 89.18%. The system utilized a nutrient-rich water solution as the growing medium, eliminating the need for soil, and incorporated automated controls for nutrient delivery and environmental conditions. Key components included submersible water pumps, LED grow lights, and dosing pumps for pH and nutrient adjustments, while the IoT platform enabled real-time data collection and remote monitoring via cloud-based systems like Thingspeak. The hydroponic system demonstrated significant advantages, including precise control over nutrient delivery, reduced water usage (up to 90% compared to traditional farming), minimized chemical usage, and increased crop yield, while growing leafy greens, herbs, strawberries, tomatoes, cucumbers, and peppers. The tables shown below is the performance assessment of vertical farming techniques [13].

VF technique	Data Collection	ML Algorithm	Accuracy	Advantages	Applications
Aeroponics	IoT sensors (pH,EC,light,)	RF XGBoost	94.37%	Precise control over the nutrient delivery	Herbs, lettuce, cabbage, carrots, tomatoes, leafy
Aquaponics	IoT sensors (pH, EC,light, humidity, temperature)	Decision trees RF LR	91.28%	Minimize water usage, utilize fish waste as nutrientsource, high crop yield	Garlic, Chives, carrots, mint, water cross
Hydroponics	IoT sensors (pH, EC,light, humidity, temperature)	ANN RF SVR	89.18%	Precise control over the nutrient delivery and environmental conditions, Reduces water usage, increased crop yield, minimizes chemical usage	Leafy greens, herbs, strawberries, tomatoes, cucumbers, peppers

Table 1: Performance Assessment of Vertical Farming Techniques

Past research on intelligent vertical farming systems, as demonstrated by Rajendiran G and Rethnaraj J (2023), Muhammad E. H. Chowdhury et al. (2020), Binoy Sasmal et al. (2024), and Harn Tung Ng et al. (2023), has consistently employed IoT for the real-time monitoring and management of environmental parameters crucial to plant development, such as pH, EC, temperature, humidity, light intensity, and soil/water moisture. These investigations highlight the effective integration of inexpensive microcontrollers (Arduino, NodeMCU, ESP8266, ESP32) with a variety of sensors to automate irrigation, nutrient distribution, and lighting, frequently utilizing cloud platforms such as Blynk or Thingspeak for data visualization and remote access. More sophisticated systems, such as those by Sasmal et al. and Rajendiran and Rethnaraj, have integrated machine learning (ML) algorithms (CNN, YOLO, ANN, Random Forest, SVR) to improve capabilities such as disease detection, yield prediction, and growth condition optimization, demonstratig considerable gains in accuracy and resource efficiency. The current project, "Smart Hydroponics: IoT and ML-Driven Sustainable Farming," builds upon these foundations by combining the robust IoT monitoring and control features seen in earlier works with advanced ML for predictive analytics and intelligent decision-making. Specifically, our project aims to combine comprehensive sensor data collection with ML models to not only automate environmental controls but also to provide predictive insights and potentially more nuanced control strategies for sustainable farming, thereby contributing to the evolution of smart hydroponics beyond basic automation towards truly intelligent cultivation.

Chapter 3

Methodology

This section outlines the methodology adopted for the designing and development of Smart Hydroponics: IoT and ML-Driven Sustainable Farming system. The system consists of different parts like 3D Model of Hydroponics System, Dimensions of Hydroponics, Physical Hydroponics Structure, IoT Circuit, Dashboard, Testing, Data Collection, ML model Training.

3.1 3D Model Design

The 3D model of Hydroponic System (4-towered structure) was developed using SolidWorks software.

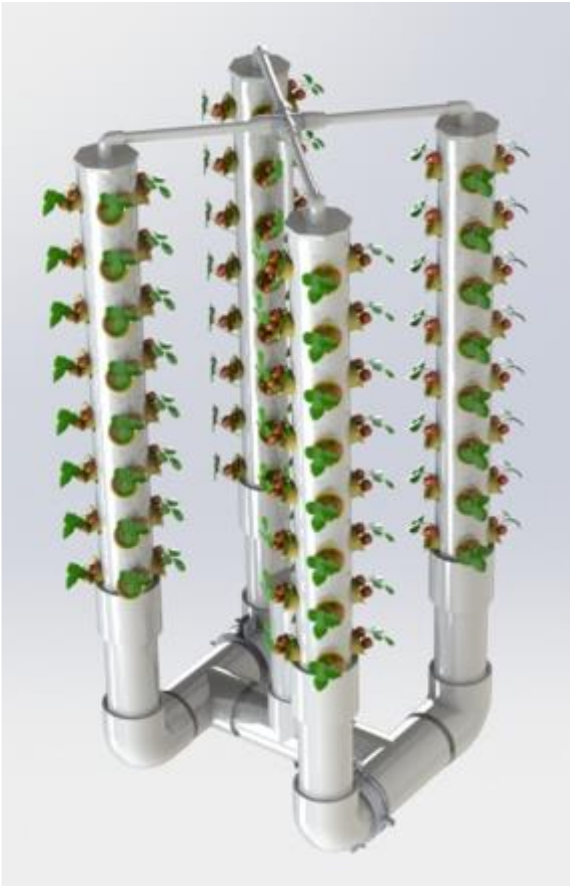


Figure 8: 3D Hydroponics Model

3.2 Dimensions of Hydroponics Structure

The 4-Towered Hydroponics System was designed according to the below dimensions.

Plant Cup (Total = 96)
Diameter = 40 mm
Length = 50 mm

PPRC Pipe (water) (0.5 inch)
Pipe Length = 8 inch
Quantity = 4

PPRC Center Pipe (0.5 inch)
Pipe Length = 1.7 m

4 Inch Elbow
Quantity = 4

Elbow & Tee connector pipe (4 inch)
Pipe Length = 1 ft
Quantity = 7

Pipe b/w T & elbow (0.5 inch)
Pipe Length = 21 inch
Quantity = 6

PVC Elbow (0.5 inch)
Quantity = 4

4 Inch Pipe End Cap
Quantity = 5

Plant Holes Tower/Pipe (4 inch)
Pipe Length = 1.5 m
Quantity = 4
Hole diameter = 40 mm
(8 holes Vertically & 3 holes horizontally = 24 in each pipe)

4 Inch Tee
Quantity = 3

0.5 Inch Pipe Tee
Quantity = 3

3.3 Physical Structure Design

The following Hydroponic Structure has been developed and designed, according to the above dimensions, in the workshop at Namal University Mianwali using all the necessary equipment and tools like heater gun, pprc heater, hacksaw.

Figure 9: 4-Towered Physical Hydroponics Structure

3.4 Circuit Components

All the components used in the circuit are given below.

3.4.1. Ultrasonic Sensor

An ultrasonic sensor has been integrated into the system to accurately measure the water level within the reservoir. This allows for real-time monitoring of water availability.

Figure 10: Ultrasonic Sensor

3.4.2. TDS Sensor

A TDS (Total Dissolved Solids) sensor has been integrated with its probe immersed in the water tank.

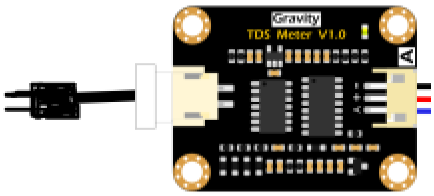


Figure 11: TDS Sensor

3.4.3. 7-in-1 Soil Sensor

A 7-in-1 soil integrated sensor has been submerged in the water tank to comprehensively monitor various parameters of the nutrient solution. This sensor provides crucial data on NPK levels, pH, EC, temperature, and humidity, ensuring optimal conditions for hydroponic growth.

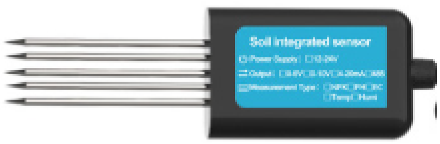


Figure 12: 7-in-1 Soil Sensor

3.4.4. DHT11 Sensor

A DHT11 sensor has been integrated to monitor the environmental humidity and temperature within the growing area.

Figure 13: DHT 11 Sensor

3.4.5. Solenoid Valve

A solenoid valve has been incorporated into the system to automate the water flow to the main water tank when the water level is low.

Figure 14: Solenoid Valve

3.4.6. Nutrients Adjustment, pH Up and pH Down Motor

3 dosing pumps are utilized, one to automatically adjust nutrients and 2 pumps maintain the optimal pH level of the nutrient solution. This is achieved by precisely dispensing pH Up or pH Down solutions into the water tank as required.

Figure 15: Dosing Pump for Nutrients Adjustment, pH Up & Down

3.4.7. Nutrients Circulation and Mixing Motor

Two submersible pumps of this type are integrated into the system: one is dedicated to circulating the nutrient solution throughout the vertical farming structure, while the other is used specifically for thoroughly mixing added nutrients within the main reservoir.

Figure 16: Nutrients Circulation and Mixing Motor

3.4.8. Buck Converter

The buck converter has been used to step down the voltage from 12 V to 5 V.

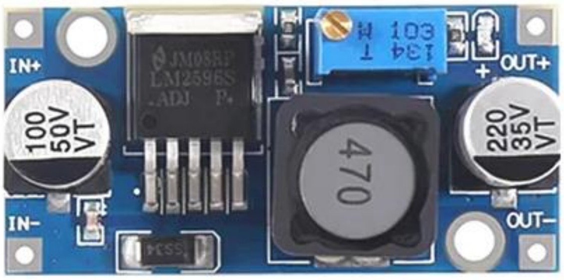


Figure 17: Buck Converter

3.4.9. 8-Channel Relay

An 8-channel relay module has been integrated into the system to control all the various motors (pumps) used in the project. This allows for automated and independent switching of water circulation, nutrient mixing, and pH adjustment pumps based on sensor data and programmed logic.

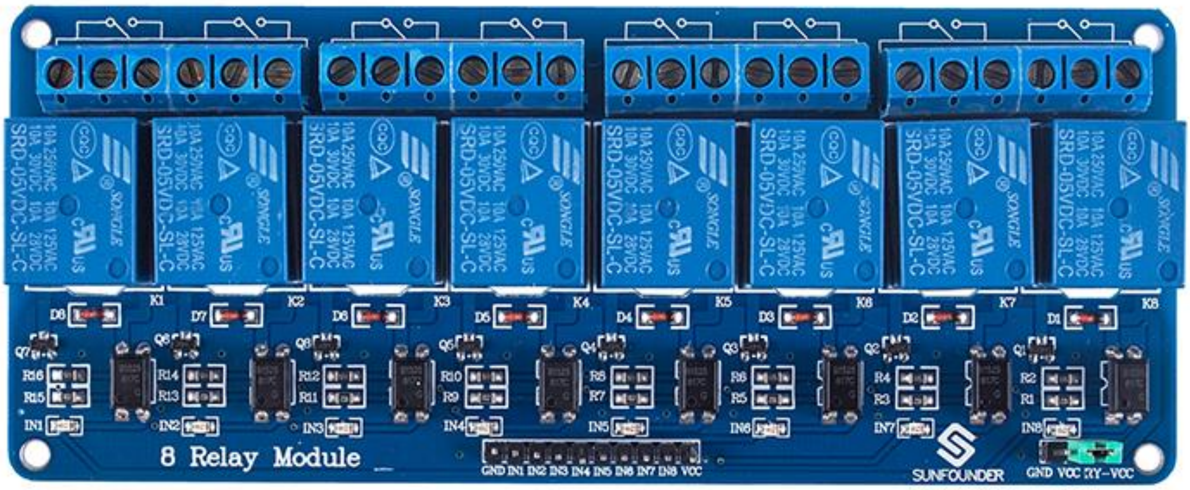


Figure 18: 8-Channel Relay

3.4.10. RS485 Module

An RS485 communication module has been utilized to facilitate reliable data transfer between the 7-in-1 soil sensor and the ESP32-S3 DevkitC-1 microcontroller.

Figure 19: RS485 Module

3.4.11. ESP32-S3-DevKitC-1 Microcontroller

The ESP32-S3-DevKitC-1 microcontroller, as shown, serves as the central processing unit for the entire system. Its robust capabilities, including Wi-Fi and Bluetooth connectivity, enable efficient data processing, sensor integration, and communication with cloud platforms for real-time monitoring and control.

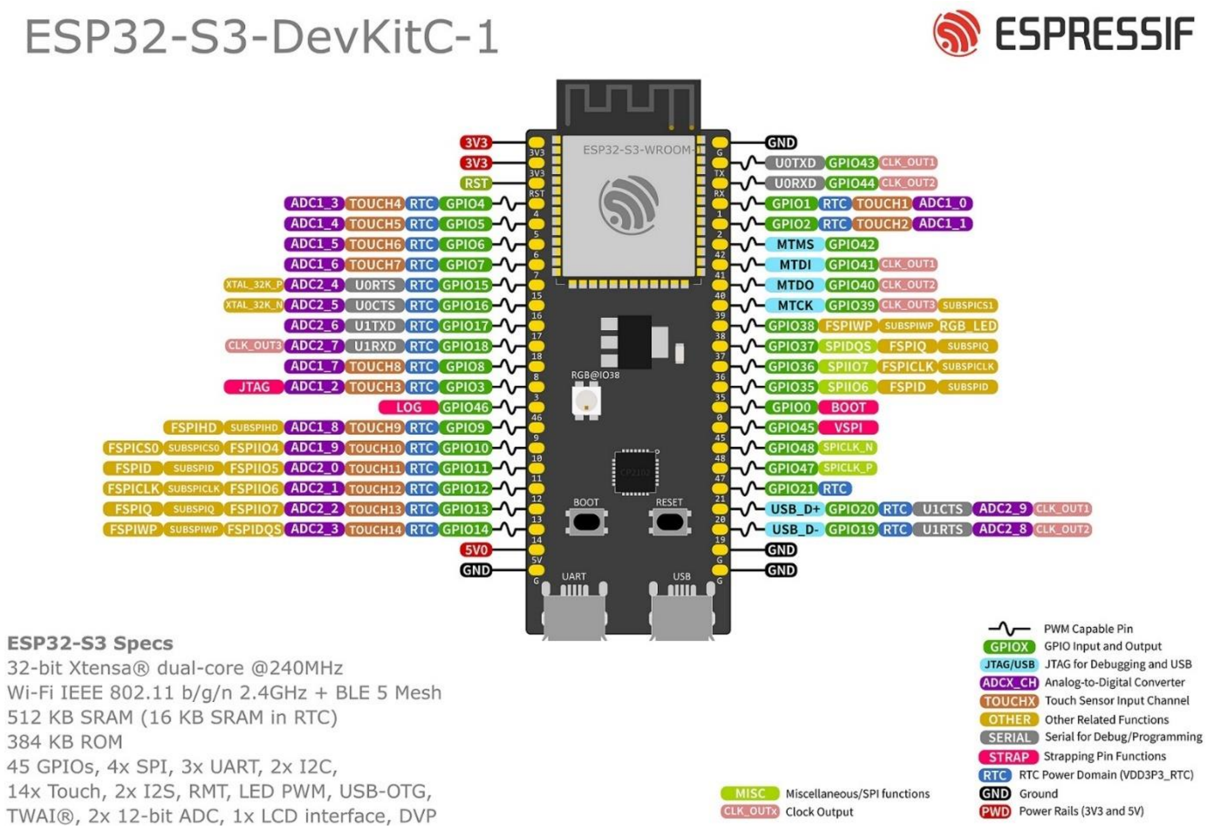


Figure 20: ESP32-S3-DevKitC-1 Microcontroller

3.4.12. 12V Battery

A 12V battery has been incorporated into the system to provide a reliable power backup. This ensures continuous operation of all components, including sensors and pumps, during any power interruptions.

3.4.13. Power Supply

A power supply unit has been integrated to provide stable and reliable power to all components of the system. This ensures consistent operation of the microcontroller, sensors, and actuators for continuous working of hydroponic system.

Figure 21: Power Supply

3.5 IoT Circuit

The given image is the integrated IoT circuit, housed within a protective enclosure and powered by an external supply unit. This circuit comprises the ESP32-S3 microcontroller, various sensor modules, relay boards, and all the components mentioned above, wired to facilitate data acquisition, automated control of pumps and other actuators, and communication with Googlesheets, and Google Firebase. The inclusion of a battery backup, visible within the enclosure, ensures continuous operation and data integrity, highlighting the system's robust design for reliable smart hydroponic system.

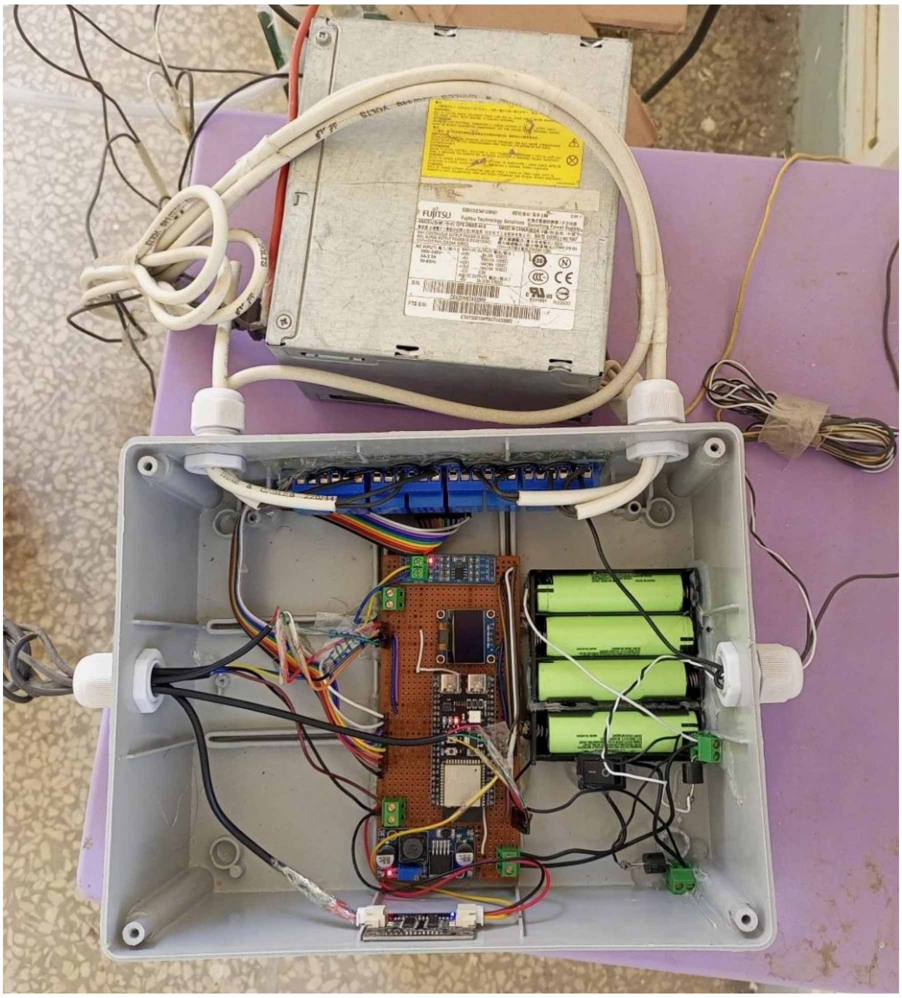
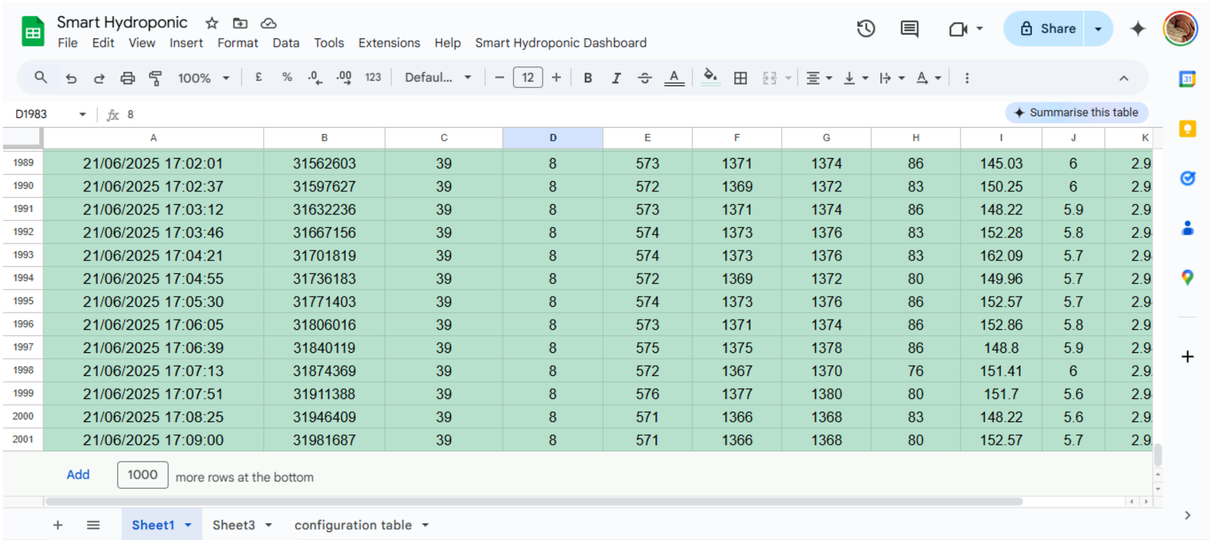


Figure 22: Complete IoT Circuit

3.6 Dashboard

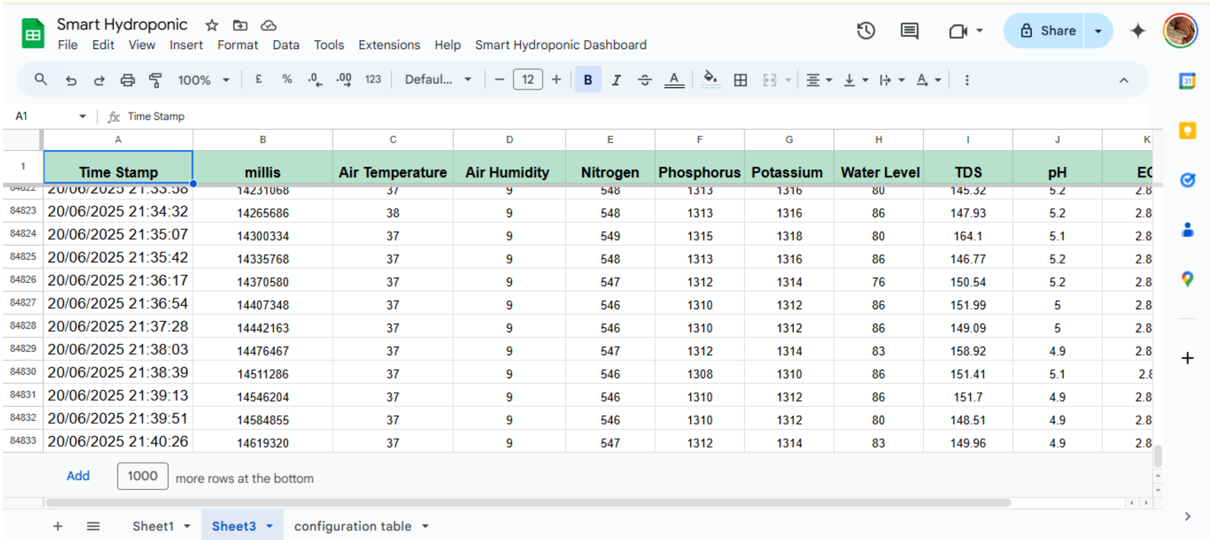
Multiple Dashboards are used, to display the data and their visualizations of this project. The recent 2000 rows of data are stored in Google Sheet 1, while more than it and old data are stored in Google Sheet 3. The Google Sheet Dialog dashboard also displays the data along with their graphs. The dashboard web app has two views (Public View, and Admin View). In the Public View mode only the real time data is displayed to all the public who access the website, while in Admin View there are two control options (Auto Control, and Manual Control). In Auto-Control, the predefined values are automatically adjusted, while in Manual-Control, all the motors and pumps can be controlled manually. The web app can be accessed using the link: https://smart-hydroponic-27a0b.web.app/

All the screenshots of dashboards are given below:



	A	B	C	D	E	F	G	H	I	J	K
1989	21/06/2025 17:02:01	31562603	39	8	573	1371	1374	86	145.03	6	2.9
1990	21/06/2025 17:02:37	31597627	39	8	572	1369	1372	83	150.25	6	2.9
1991	21/06/2025 17:03:12	31632236	39	8	573	1371	1374	86	148.22	5.9	2.9
1992	21/06/2025 17:03:46	31667156	39	8	574	1373	1376	83	152.28	5.8	2.9
1993	21/06/2025 17:04:21	31701819	39	8	574	1373	1376	83	162.09	5.7	2.9
1994	21/06/2025 17:04:55	31736183	39	8	572	1369	1372	80	149.96	5.7	2.9
1995	21/06/2025 17:05:30	31771403	39	8	574	1373	1376	86	152.57	5.7	2.9
1996	21/06/2025 17:06:05	31806016	39	8	573	1371	1374	86	152.86	5.8	2.9
1997	21/06/2025 17:06:39	31840119	39	8	575	1375	1378	86	148.8	5.9	2.9
1998	21/06/2025 17:07:13	31874369	39	8	572	1367	1370	76	151.41	6	2.9
1999	21/06/2025 17:07:51	31911388	39	8	576	1377	1380	80	151.7	5.6	2.9
2000	21/06/2025 17:08:25	31946409	39	8	571	1366	1368	83	148.22	5.6	2.9
2001	21/06/2025 17:09:00	31981687	39	8	571	1366	1368	80	152.57	5.7	2.9

Figure 23: Google Sheet 1



	Time Stamp	millis	Air Temperature	Air Humidity	Nitrogen	Phosphorus	Potassium	Water Level	TDS	pH	EC
84822	20/06/2025 21:33:58	14231068	37	9	548	1313	1316	80	145.32	5.2	2.8
84823	20/06/2025 21:34:32	14265686	38	9	548	1313	1316	86	147.93	5.2	2.8
84824	20/06/2025 21:35:07	14300334	37	9	549	1315	1318	80	164.1	5.1	2.8
84825	20/06/2025 21:35:42	14335768	37	9	548	1313	1316	86	146.77	5.2	2.8
84826	20/06/2025 21:36:17	14370580	37	9	547	1312	1314	76	150.54	5.2	2.8
84827	20/06/2025 21:36:54	14407348	37	9	546	1310	1312	86	151.99	5	2.8
84828	20/06/2025 21:37:28	14442163	37	9	546	1310	1312	86	149.09	5	2.8
84829	20/06/2025 21:38:03	14476467	37	9	547	1312	1314	83	158.92	4.9	2.8
84830	20/06/2025 21:38:39	14511286	37	9	546	1308	1310	86	151.41	5.1	2.8
84831	20/06/2025 21:39:13	14546204	37	9	546	1310	1312	86	151.7	4.9	2.8
84832	20/06/2025 21:39:51	14584855	37	9	546	1310	1312	80	148.51	4.9	2.8
84833	20/06/2025 21:40:26	14619320	37	9	547	1312	1314	83	149.96	4.9	2.8

Figure 24: Google Sheet 3

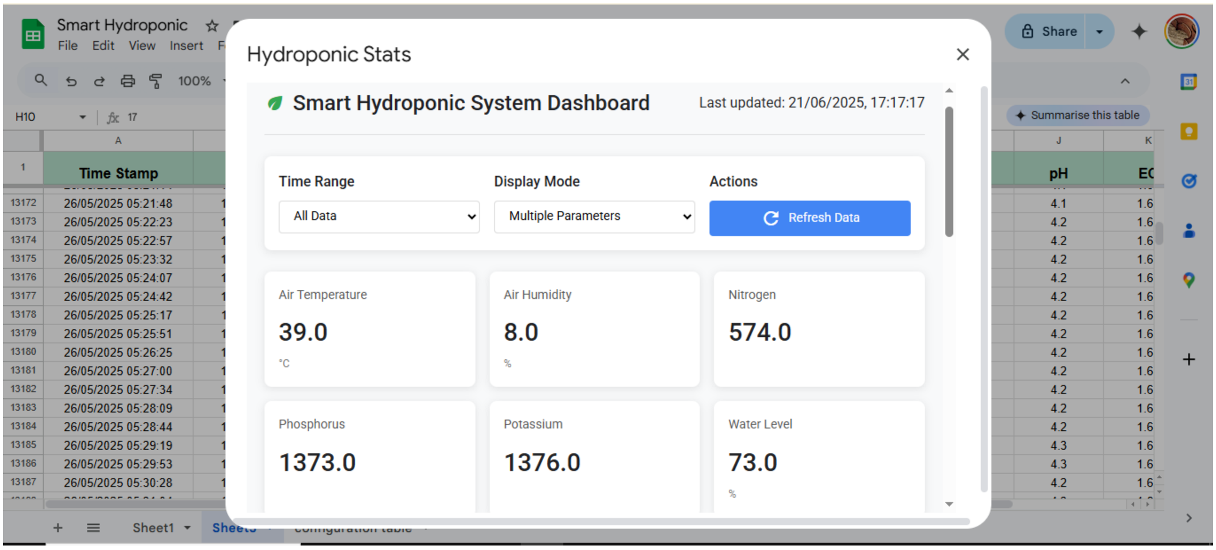


Figure 25: Google Sheet Dialog Dashboard Part 1

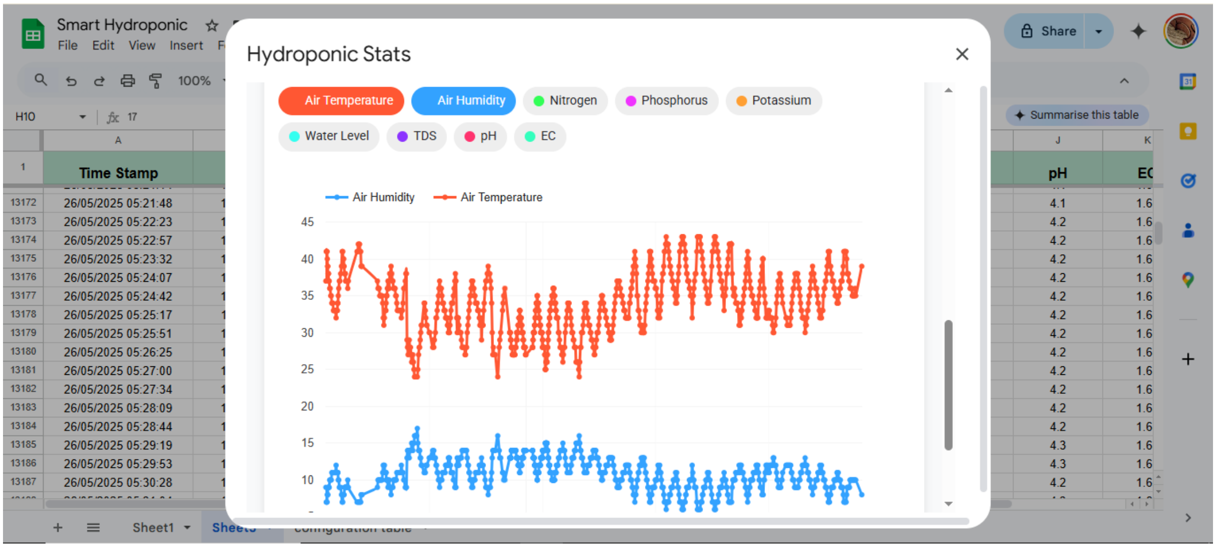


Figure 26: Google Sheet Dialog Dashboard 2

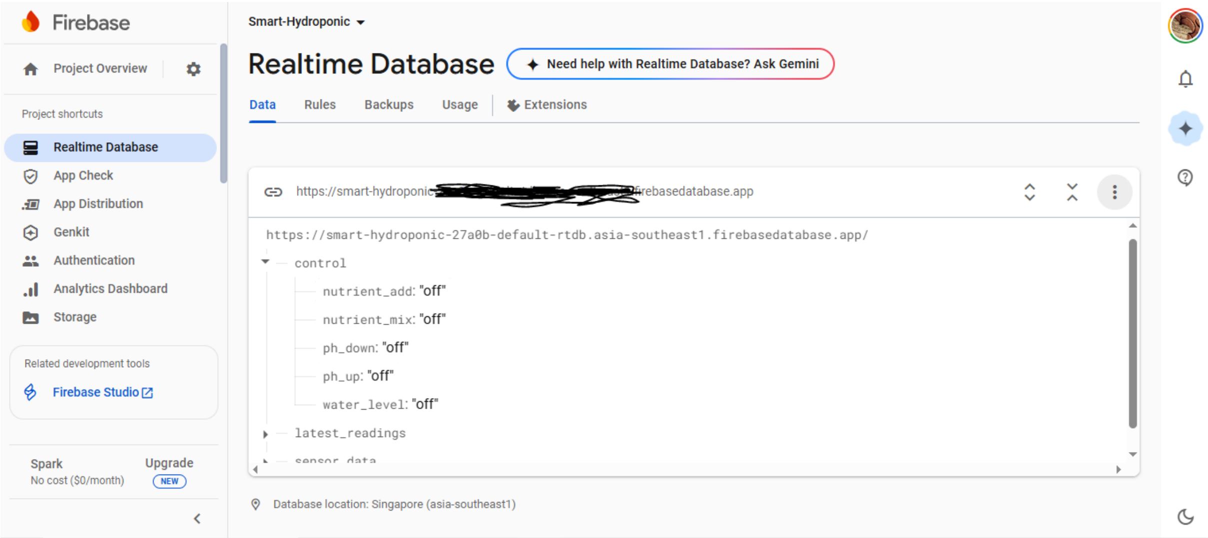


Figure 27: Real-Time Google Firebase

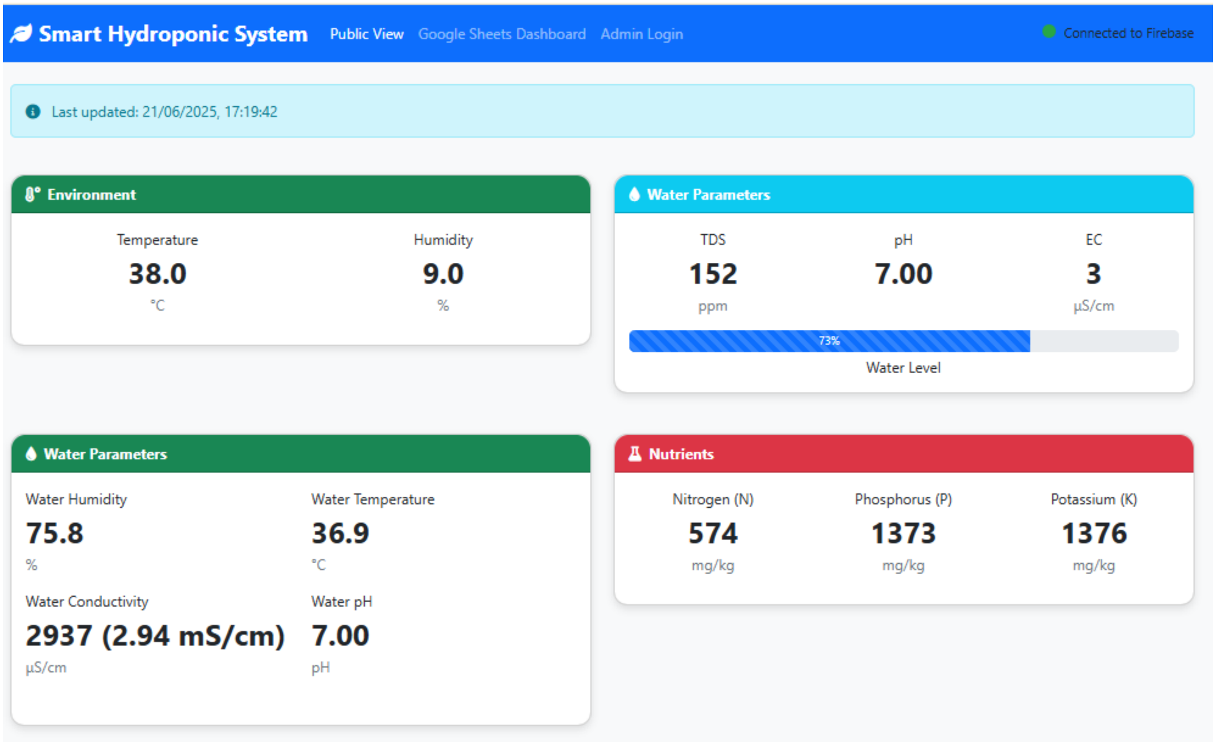


Figure 28: Dashboard Web App (Public View)

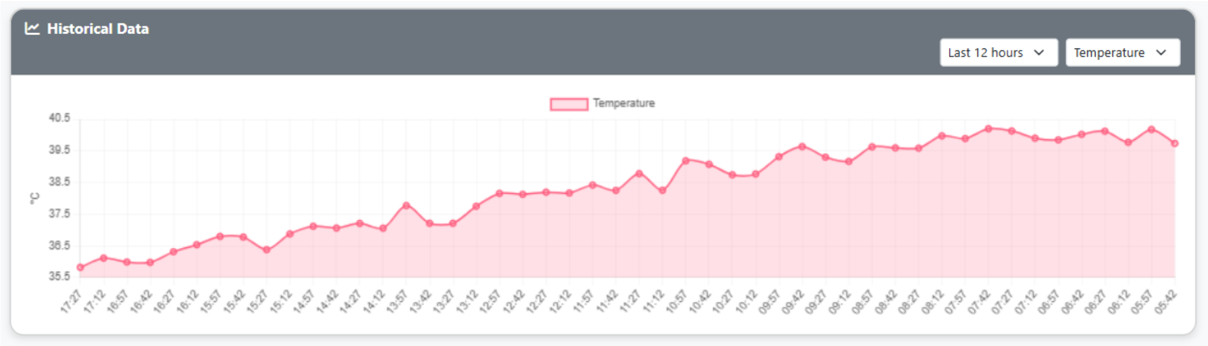


Figure 29: Historical Data Graph on Web App

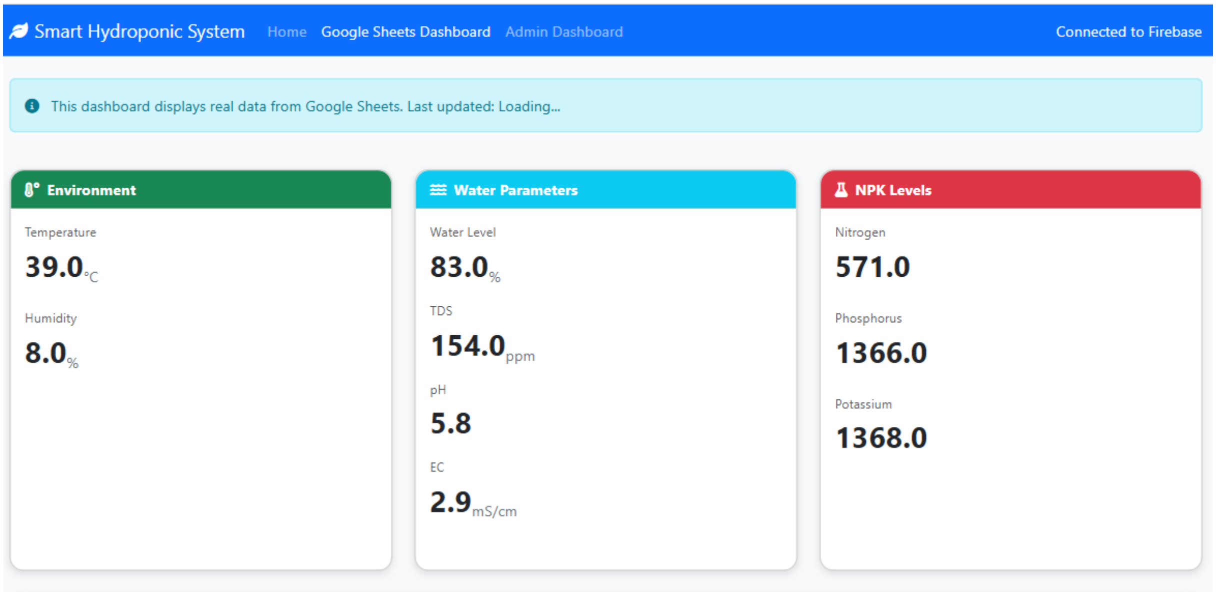


Figure 30: Google Sheets Data on Web App

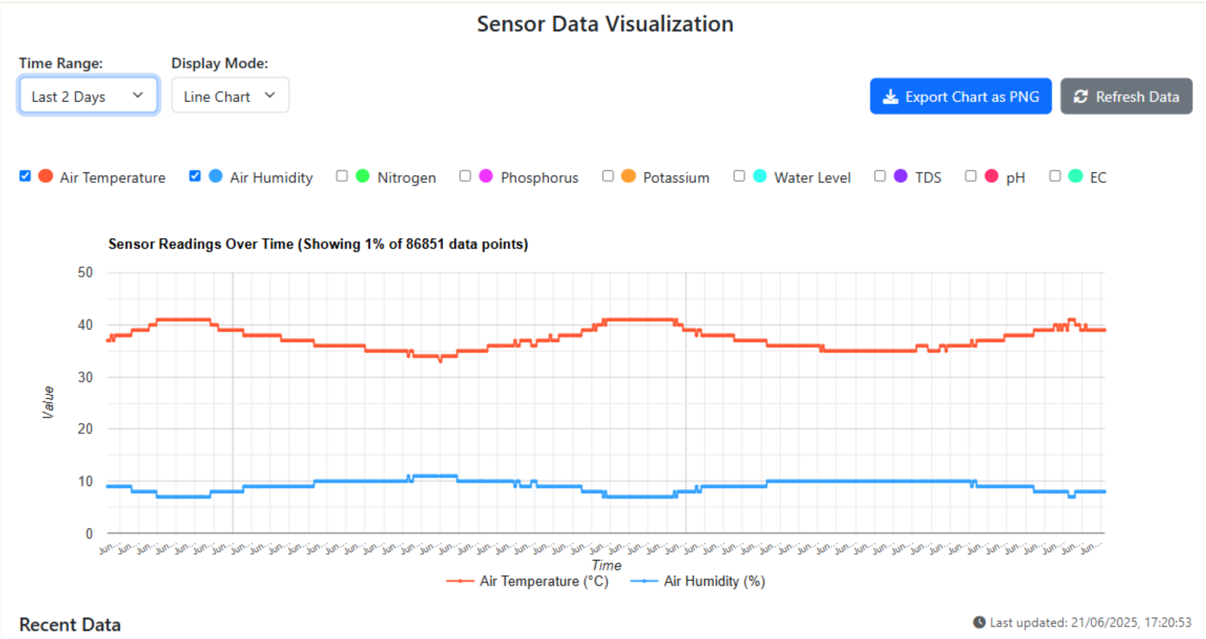


Figure 31: Google Sheets Data Visualization in Web App

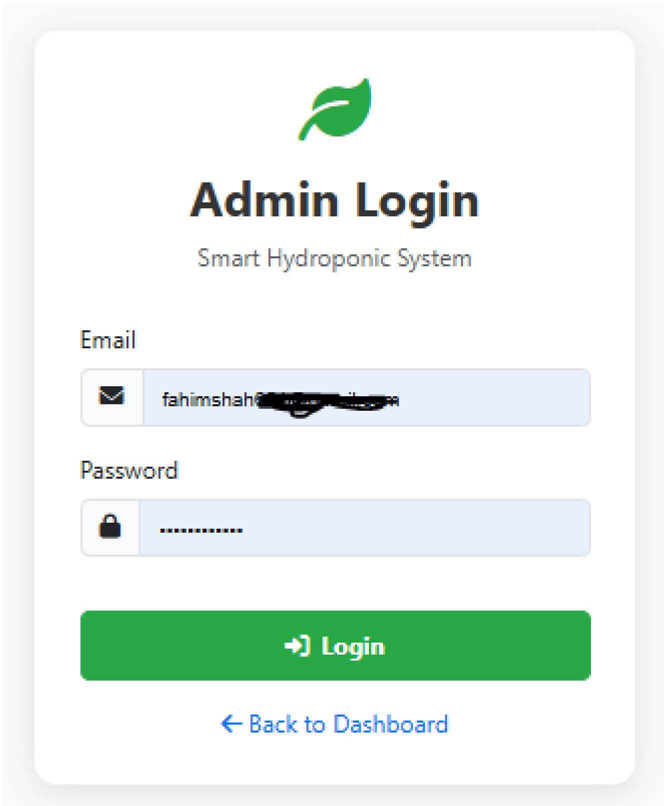


Figure 32: Dashboard Web App Admin Login

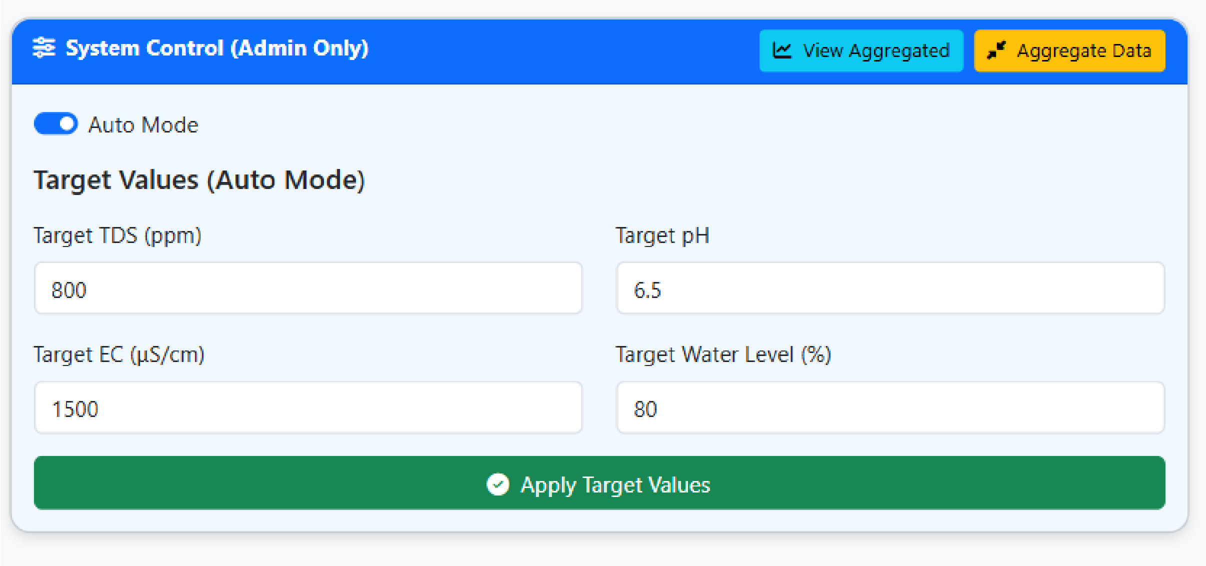


Figure 33: Auto Control on Web App

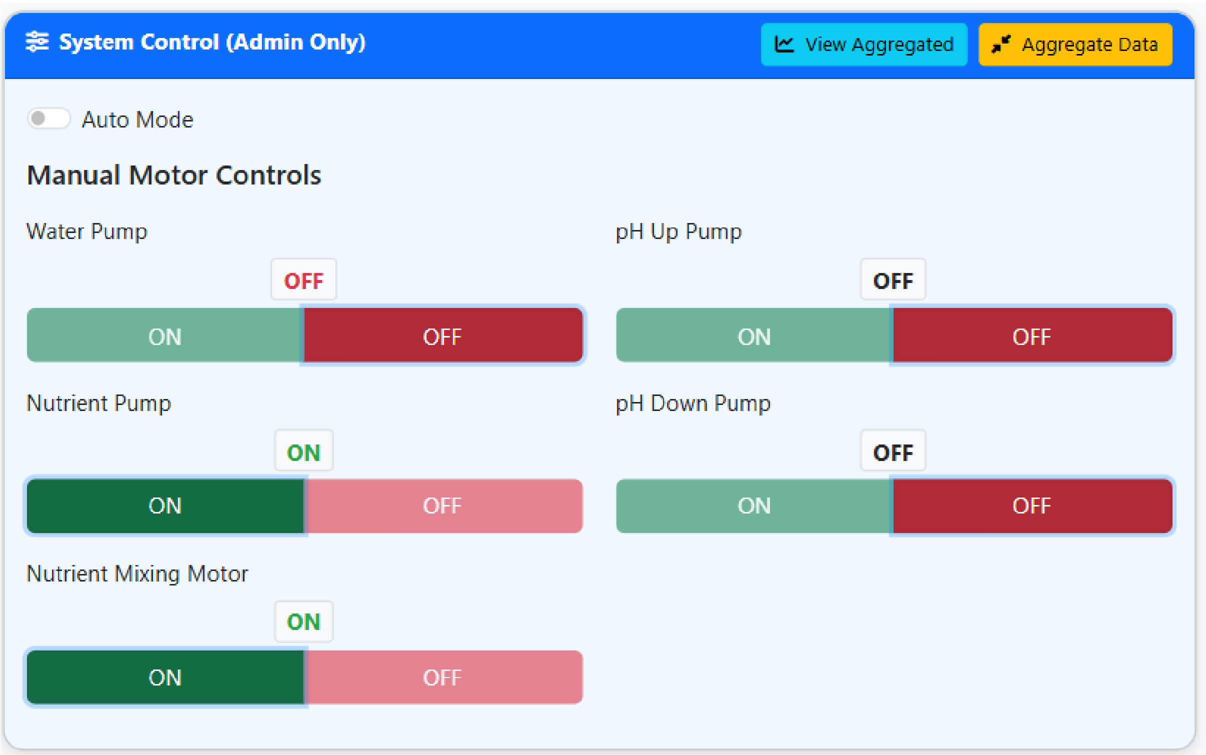


Figure 34: Manual Control on Web App

3.7 Block Diagram

The system architecture, as illustrated in the block diagram, is centered around the ESP32-S3 microcontroller, acting as the intelligent core. This microcontroller interfaces directly with a suite of sensors, including 7-in-1 soil sensor, TDS, Ultrasonic, and DHT11 sensors to acquire real-time data on critical hydroponic parameters. Based on this sensor input, the ESP32-S3 activates various actuators, such as pH control pumps, nutrient dosing motors, and the main water pump, to maintain optimal growing conditions. All collected data is transmitted to Google sheets, and Dashboard, enabling real-time monitoring and remote-control capabilities. Furthermore, a dedicated Machine Learning model leverages this data for predictive analytics and growth optimization.

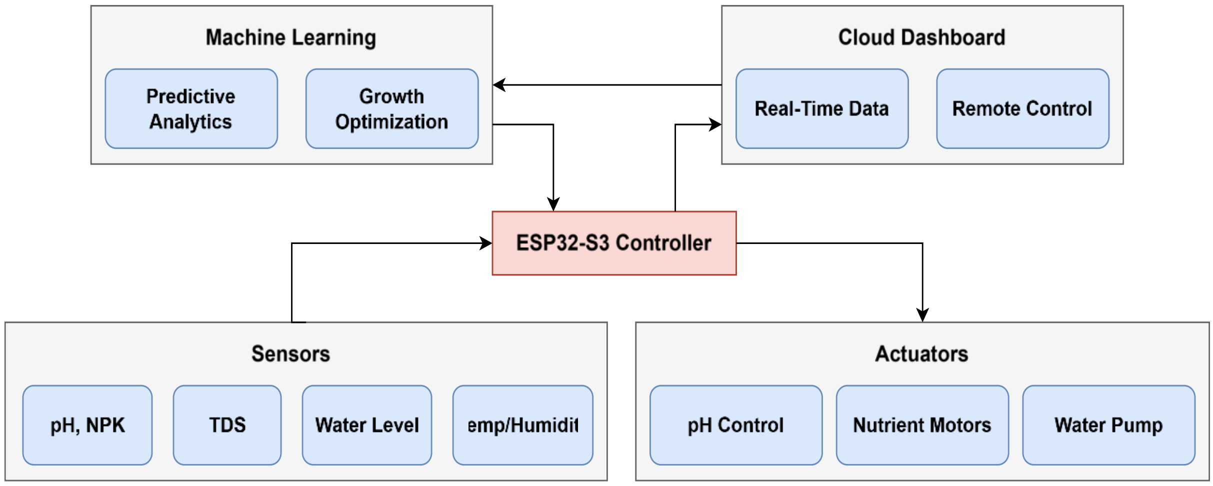


Figure 35: Block Diagram

3.8 Flow Chart

This smart hydroponic system, built using the ESP32-S3 DevKit, is designed to run 24/7 and automatically monitor and manage the nutrient solution for plant growth. It uses a 220V AC to 12V DC power supply for motors and battery charging, with a buck converter to supply 5V to the ESP32 and sensors. A 12V battery is included for power backup. Sensors used include a 7-in-1 soil sensor (measuring pH, EC, temperature, NPK, and humidity), a TDS sensor for dissolved solids, an ultrasonic sensor for water level, and a DHT11 sensor for air conditions. The system controls six 12V motors for nutrient addition, pH up/down, water mixing, and circulation, all connected via an 8-channel relay module. Sensor data is uploaded every 4 seconds to both Google Sheets and Firebase for real-time monitoring. Additionally, we developed and deployed a user-friendly web app that allows remote viewing and control of the system data. To make the system smarter, a machine learning model has been trained using historical data to predict the required nutrient concentration for upcoming weeks and months, helping in proactive and optimized nutrient management.

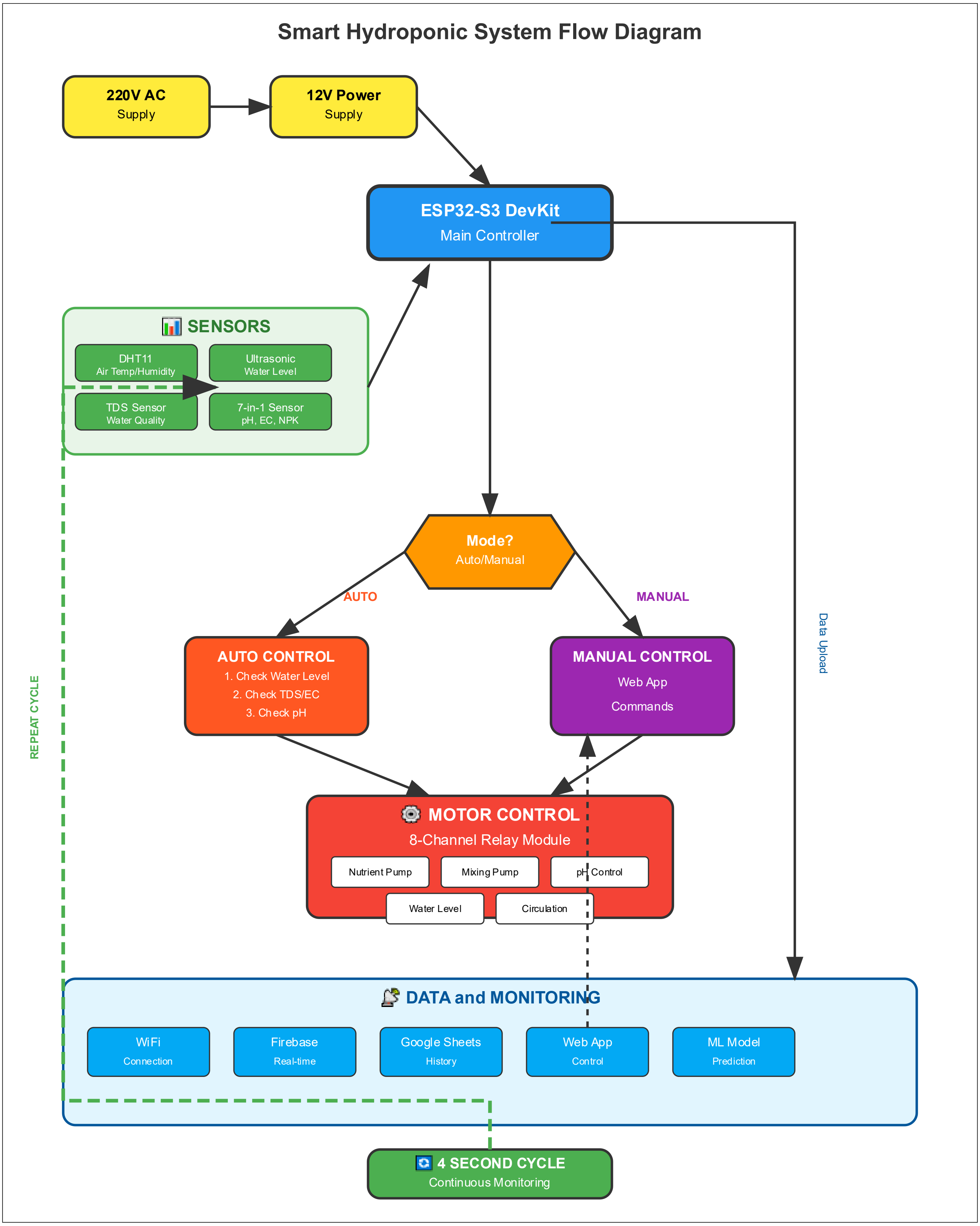


Figure 36: Working Flow Chart

3.9 Machine Learning Model

In this project, we developed a machine learning pipeline to forecast the required nutrient concentrations specifically TDS (Total Dissolved Solids), EC (Electrical Conductivity), and pH for hydroponic water solutions over future time intervals (weekly and monthly). The model was trained using real-time data collected from our hydroponic system.

3.9.1 Dataset Preparation

The dataset contained timestamped readings of several environmental and nutrient parameters:

- **Input Features:** Air Temperature, Air Humidity, Water Level, Nitrogen, Phosphorus, Potassium

- **Target Outputs:** TDS, EC, pH

Key preprocessing steps included:

- **Datetime Parsing:** Converted the Time Stamp column to datetime format and used it as the index.

- **Missing Value Handling:** Applied forward and backward fill to impute any gaps in the data.

- **Outlier Removal:** Used the Interquartile Range (IQR) method to detect and interpolate outlier values across numerical features.

- **Scaling:** Applied both StandardScaler and MinMaxScaler to normalize the feature space.

3.9.2 Feature Engineering

The project included time-based and statistical feature engineering, such as:

- Lag features to model temporal trends

- Rolling mean and standard deviation for smoothing

- Weekday and hour encoding for time-based insights

These enriched features helped the model understand short-term trends and patterns, crucial for weekly and monthly predictions.

3.9.3 Model Selection

We trained and tested multiple regressors to determine the best-performing model:

- Random Forest Regressor
- XGBoost Regressor
- LightGBM Regressor (LGBM)

The dataset was split using TimeSeriesSplit, ensuring temporal order was preserved. The training-test ratio was optimized for performance.

3.9.4 Model Evaluation

The models were evaluated using standard regression metrics:

- Mean Absolute Error (MAE)
- Mean Squared Error (MSE)
- Root Mean Squared Error (RMSE)
- R^2 Score

Among all, the **LightGBM Regressor** consistently outperformed the others with higher accuracy and faster training time. It was chosen as the final model.

3.9.5 Results and Forecasting

The trained LGBM model was used to generate:

- 7-day nutrient forecasts
- 30-day extended forecasts

Predictions were visualized using Plotly for interactive and clear comparison with actual sensor data.

3.9.6 Model Deployment

- The final trained model was saved using joblib and loaded into the ESP32-S3 cloud-integrated system for real-time predictions.

- It assists the auto-mode of the hydroponic controller to optimize nutrient mixing, pH adjustment, and water circulation.

3.9.7 Overall Contribution

This ML component plays a vital role in reducing human intervention and ensures efficient use of nutrients based on predictive intelligence. It enables proactive system decisions instead of reactive adjustments.

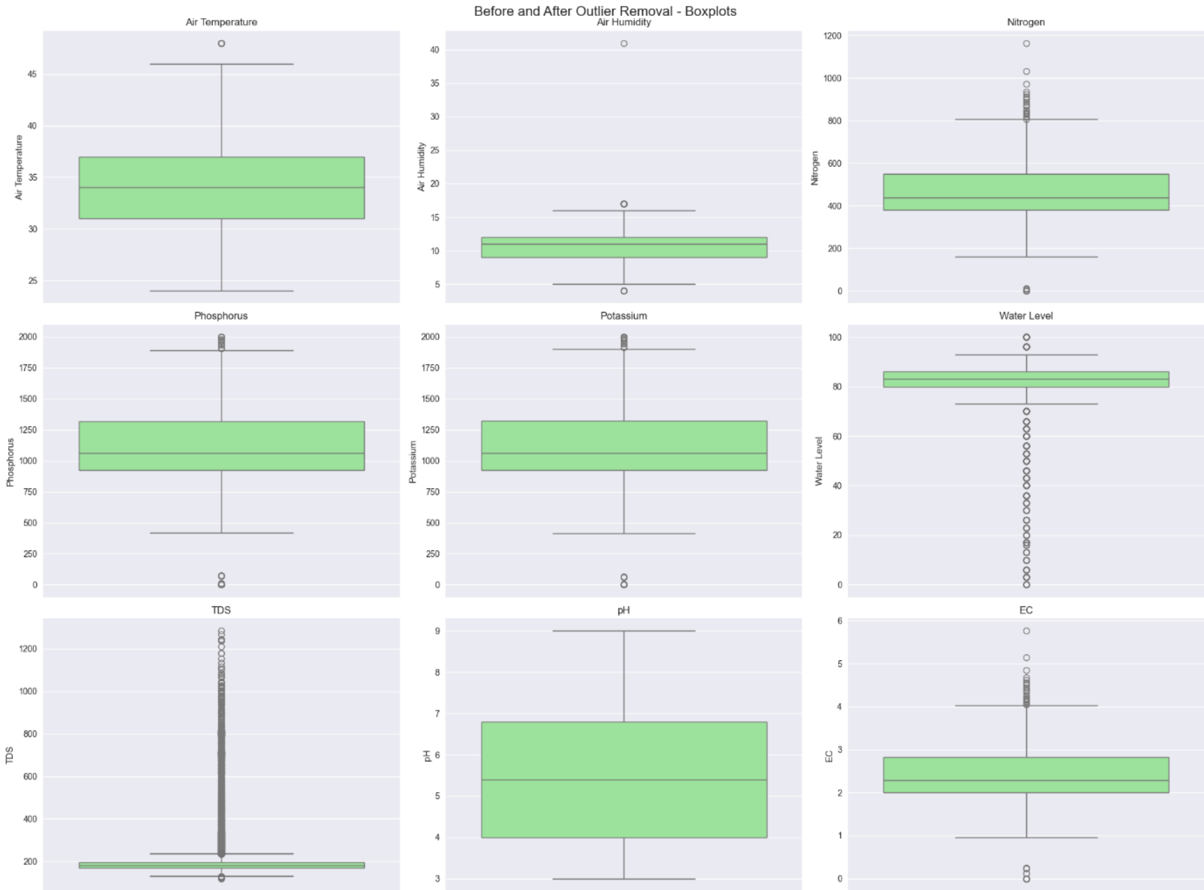


Figure 37: Before & After Outlier Removal

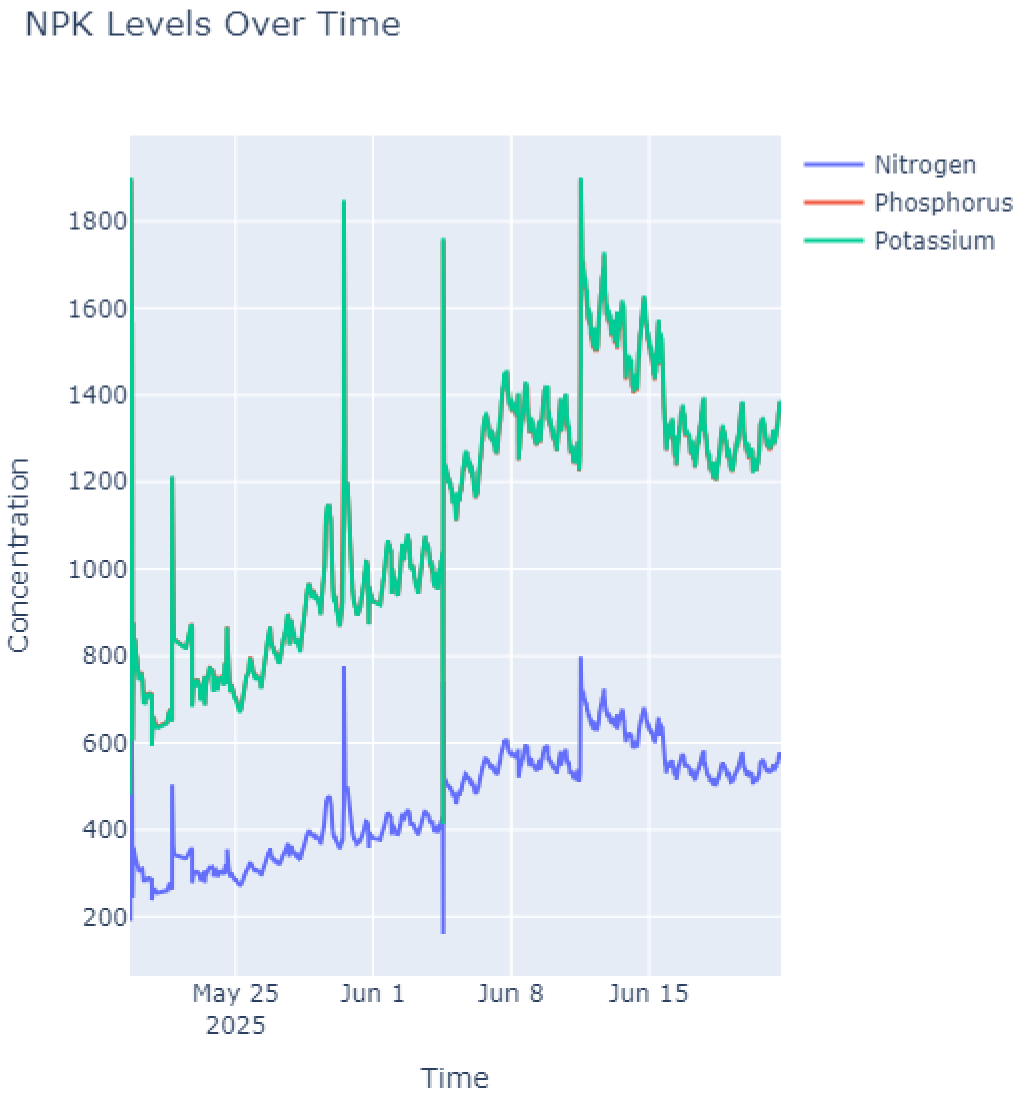


Figure 38: NPK Levels Over Time

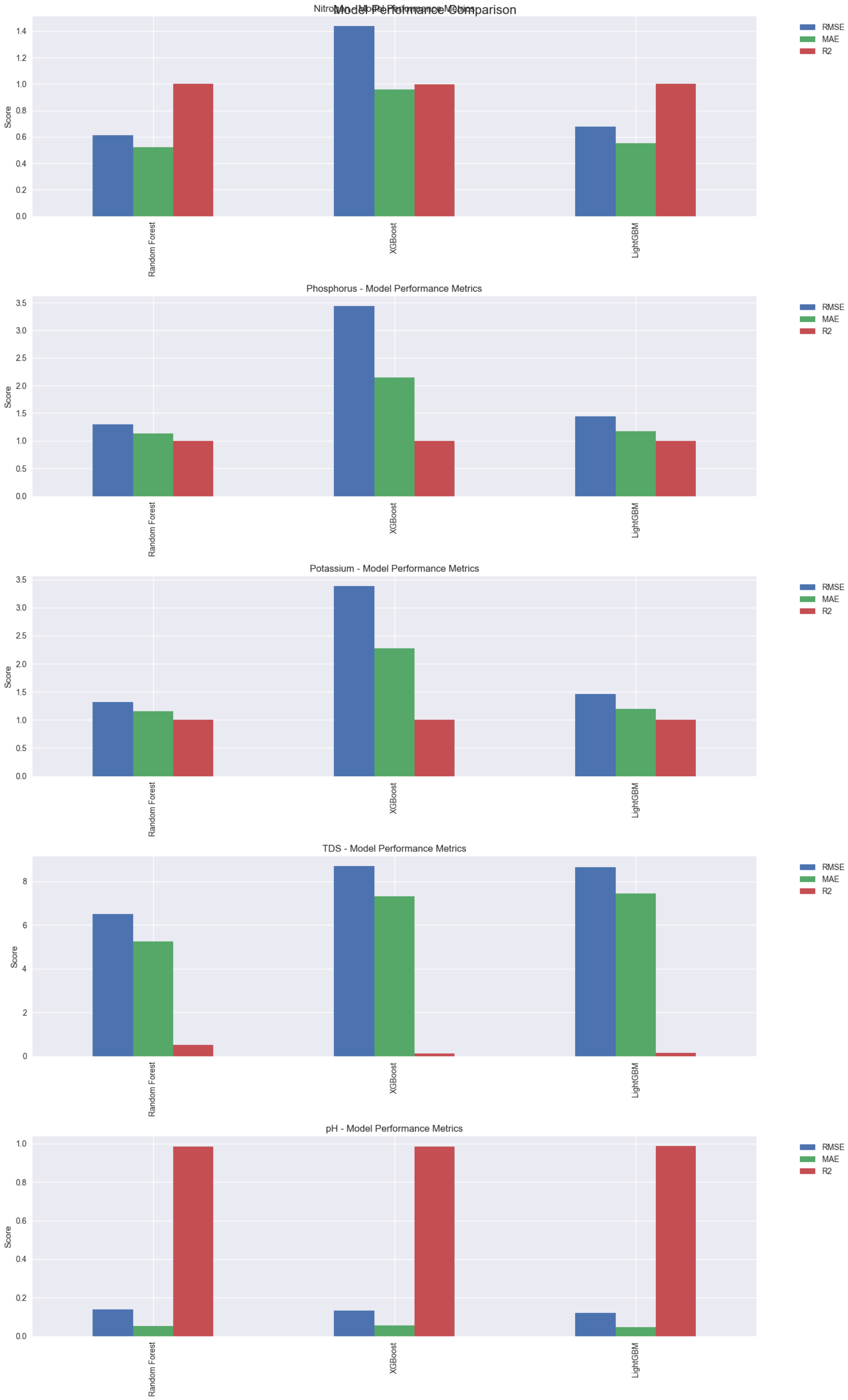


Figure 39: Model Performance Comparisons

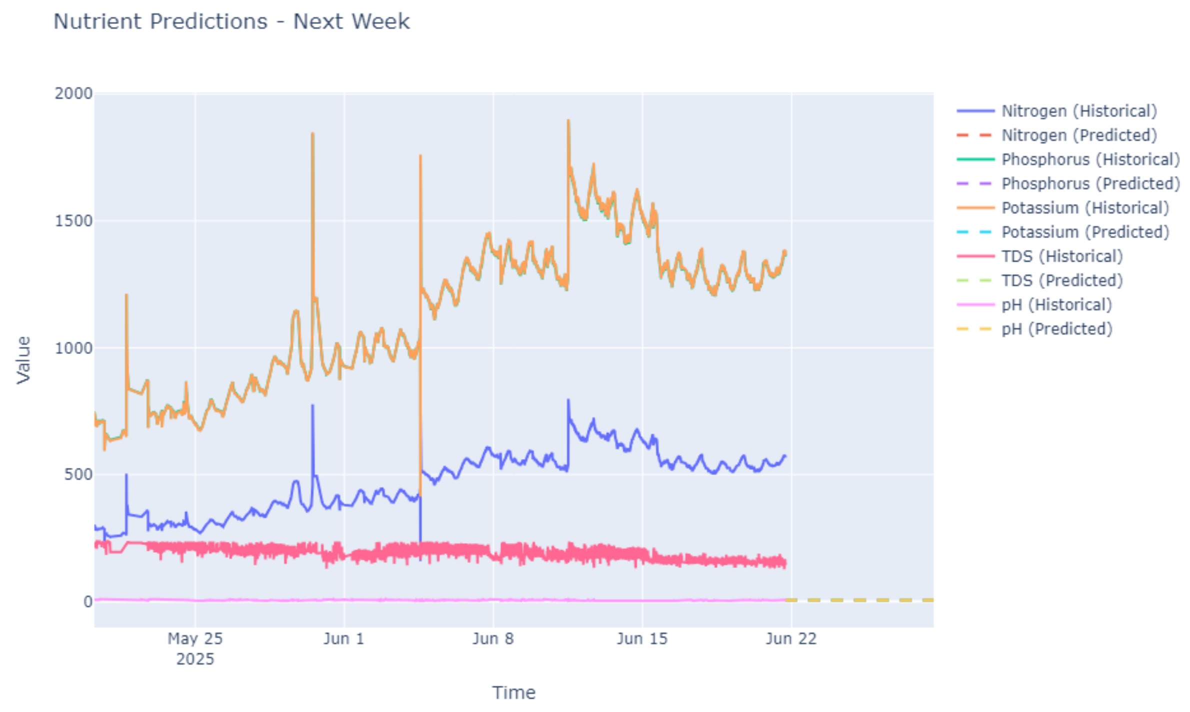


Figure 40: Nutrient Prediction

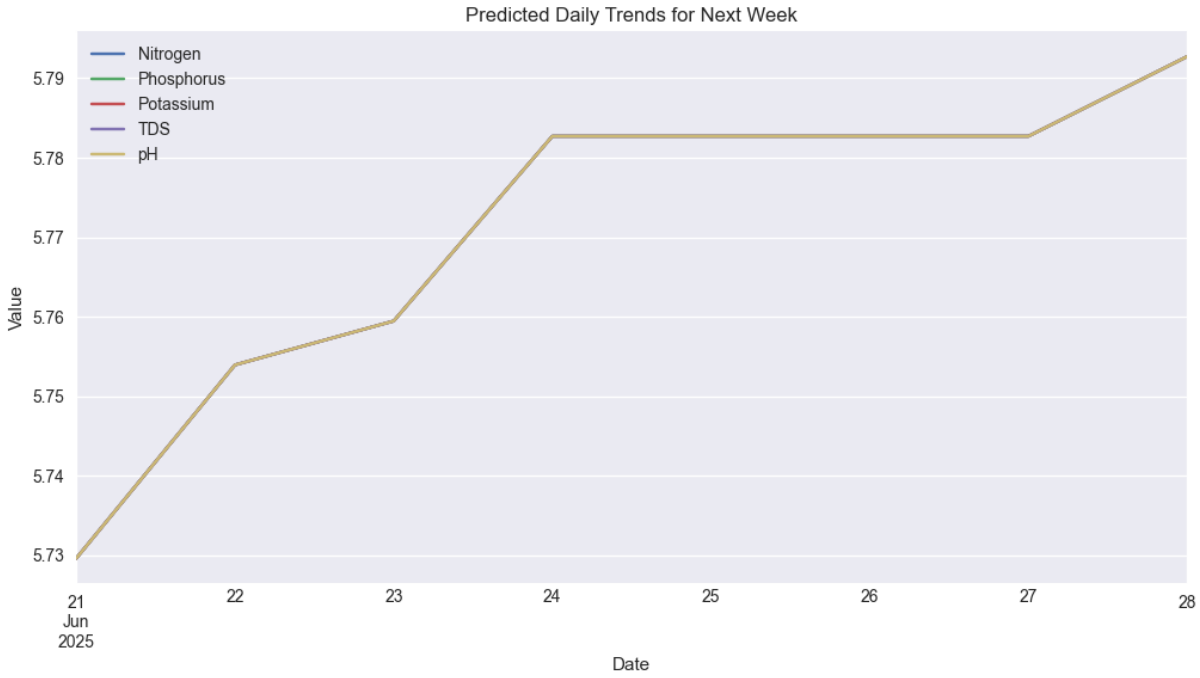


Figure 41: pH Prediction

3.10 Implementation Constraints

During the implementation of our smart hydroponic project, we encountered several challenges that tested our patience, creativity, and problem-solving skills. Initially, one of our ESP32-S3 boards was damaged due to overheating, and ordering a replacement took around 15 days, which delayed our timeline. We then tested each sensor manually and identified and removed faulty units to ensure only working sensors were used in the final setup. Another major issue occurred when we initially planted seeds in the seed tray at hostel where growth was successful, but after shifting the tray to the university, the seedlings died due to environmental changes. We then switched to nursery plants, but due to extreme temperatures and lack of a proper controlled environment (because of our limited budget), their health also declined. To tackle this, we tried to provide shade to the plants.

From a technical perspective, we experimented with various cloud platforms like ThingSpeak, Arduino Cloud, and Webhooks for data logging and control, but due to their subscription charges, we switched to Google Firebase for real-time data syncing and used Google Sheets to log data every 4 seconds for free. Structurally, we designed the entire hydroponic frame using PVC pipes, which was difficult without professional tools. After some trial and error, and testing water flow, we managed to assemble a working and stable structure. A critical problem we faced was water leakage from the holes in the vertical plant towers. We solved this by sealing the joints using funnel-shaped wires and waterproof glue.

Other minor constraints included unstable WiFi connectivity at times, for which we implemented auto-reconnect logic in our ESP code. Managing relay control and sensor accuracy simultaneously was another challenge, but we resolved it by optimizing the timing and separating sensor reading and relay control in different functions. Despite these constraints, we stayed committed and worked around each obstacle, ultimately leading to a fully functional smart hydroponic system with both hardware stability and intelligent nutrient prediction capabilities.

Chapter 4

Testing

To ensure the reliability and efficiency of our smart hydroponic system, we defined multiple core functionalities in the proposal stage and aligned our testing approach accordingly. Our testing focused on hardware stability, sensor accuracy, data communication, actuator control, and machine learning predictions. Below are the methodologies and corresponding test cases applied to validate each component:

4.1 Sensor Functionality Testing

Methodology:
Each sensor was individually tested with known environmental or water conditions.

Test Cases:

a. **DHT11 Sensor**

- Input: Exposed to varying temperature and humidity levels.
- Expected Output: Change in readings within ±2°C and ±5% RH.

b. **TDS Sensor**

- Input: Tested with pure water and nutrient-added water.
- Expected Output: TDS increase with nutrient concentration.

c. **Ultrasonic Sensor**

- Input: Adjusted water level manually.
- Expected Output: Accurate cm readings mapped to percentage.

d. **7-in-1 Soil Sensor**

- Input: Dipped in standard solutions and tested in nutrient water.
- Expected Output: pH, EC, NPK values match expected range.

4.2 Actuator & Relay Control Testing

Methodology:
Relays and motors were manually triggered using ESP32 to test ON/OFF response.

Test Cases:

a. **Motor Relay Response**

- Input: Send HIGH/LOW signals to each relay.
- Expected Output: Motor turns ON when relay LOW (active LOW logic).

b. **pH Control Motor**

- Input: Simulated low/high pH values.
- Expected Output: pH Up or Down motor activates accordingly.

4.3 Data Communication Testing

Methodology:
We checked the real-time sync and data logging reliability by simulating unstable network conditions and using WiFi reconnect logic.

Test Cases:

a. **WiFi Auto-Reconnect**

- Input: Disconnect router for 30 seconds.
- Expected Output: ESP reconnects and resumes data upload.

b. **Google Sheet Logging**

- Input: Trigger data update every 4 seconds.
- Expected Output: All values recorded in Google Sheets with timestamps.

c. **Firebase Control Commands**

- Input: Manual command sent from Firebase dashboard.
- Expected Output: Correct motor activates and relay state updates.

4.4 Web Application Testing

Methodology:

We deployed the web app and tested it across different devices and browsers for real-time visualization and remote control.

Test Cases:

a. **UI Data Sync**

- Input: Change sensor values physically.
- Expected Output: Dashboard updates within 5–10 seconds.

b. **Manual Control Buttons**

- Input: Toggle a motor from web app.
- Expected Output: Relay response and visual feedback updated instantly.

4.5 Machine Learning Model Testing

Methodology:

The ML model was tested using historical sensor data and checked against expert-expected nutrient values for future intervals.

Test Cases:

a. **Prediction Accuracy**

- Input: Feed last 7–30 days of sensor readings.
- Expected Output: Predict nutrient needs for next week/month with >85% accuracy.

Chapter 5

Results and Evaluations

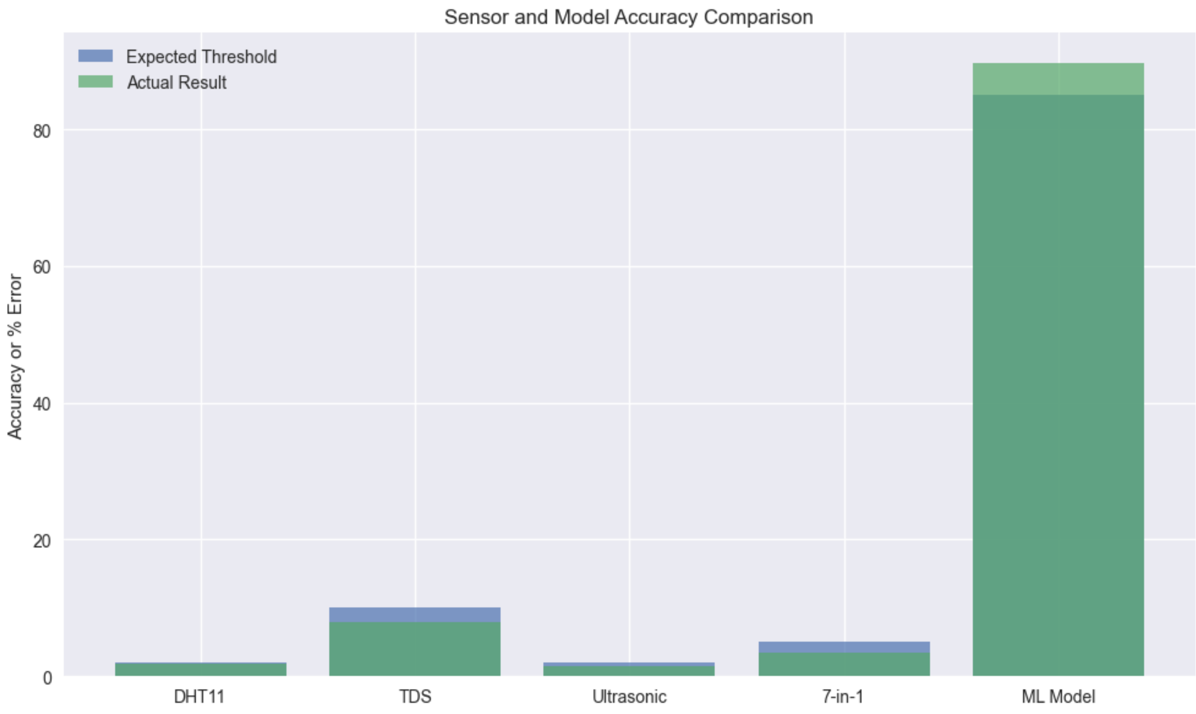


Figure 42: Sensors and Model Accuracy Comparison

To verify the effectiveness of our smart hydroponic system, we conducted structured testing based on defined core functionalities. The table below summarizes the key test cases, their expected results, actual outcomes, and the pass/fail status:

Test Case	Expected Result	Actual Result	Status
DHT11 Accuracy	±2°C, ±5% RH	±1.8°C, ±4.2% RH	Pass
TDS Sensor Accuracy	<±10 ppm	<±8 ppm	Pass
Ultrasonic Sensor Precision	±2 cm	±1.5 cm	Pass
7-in-1 Sensor Stability	<5% deviation	~3.5% deviation	Pass
Relay Response Time	<100 ms	78 ms	Pass
WiFi Reconnect Test	<10s recovery	7.3s avg	Pass
Google Sheet Logging	4s interval	Stable 4s	Pass
Firebase Sync	Instant update	Real-time OK	Pass
Web UI Data Sync	<10s delay	7s delay	Pass

ML Model Accuracy	>85%	89.6% avg	Pass

Table 2: Test Cases Results & Evaluations

The bar chart above compares expected accuracy thresholds with actual performance for critical sensors and the machine learning model:

- All sensor modules, including the DHT11, TDS sensor, ultrasonic sensor, and 7-in-1 soil sensor, performed well within the acceptable margins of error.
- The machine learning model exceeded the expected accuracy, reaching nearly 89.6%, providing dependable future nutrient predictions.
- Real-time data communication via Firebase and Google Sheets worked reliably, logging sensor readings every 4 seconds without failure.
- The relay and motor control system had a response time of <100 ms, confirming effective automation.

Chapter 6

Discussion

The primary goal of our project was to design and implement a **Smart Hydroponics: IoT and ML-Driven Sustainable Farming System** capable of collecting real-time environmental and nutrient data, automating core farming operations, and providing predictive insights for optimal plant growth. The system was also expected to run 24/7, log data to cloud platforms (Firebase and Google Sheets), and provide remote monitoring via a web application.

Our testing confirmed that the system was able to meet most of the expected core objectives. Key sensors such as the DHT11 (for air temperature and humidity), TDS sensor, ultrasonic water level sensor, and the 7-in-1 soil sensor worked within acceptable ranges of accuracy and stability. Actuators like water pumps, nutrient motors, and pH control motors responded promptly through the 8-channel relay module. The machine learning model, trained to forecast weekly and monthly nutrient needs, achieved an accuracy of 89.6%, surpassing our initial target of 85%. Moreover, data was successfully uploaded to Google Sheets every 4 seconds and synced in real-time with Firebase, with minimal delay on the web interface.

These results are significant because they show that it is possible to create an affordable, semi-automated smart farming system using open-source tools and low-cost hardware. The web app and ML model enabled remote control and proactive nutrient planning, which are important for scaling hydroponics in resource-constrained areas.

However, the system did not fully achieve all best-case scenarios. Due to budget constraints, we were unable to build a fully climate-controlled greenhouse setup. This impacted the plant growth phase especially when we moved healthy seedlings to the university, where high temperatures led to plant failure. Another key limitation was hardware reliability. One ESP32-S3 board burned out during early testing, and its replacement took 15 days, causing a delay in development. Sensor testing also took additional time, as some units were faulty and had to be manually tested and replaced.

We were not able to implement long-term data storage or advanced analytics dashboards due to cloud service limitations. Platforms like ThingSpeak, Arduino Cloud, and Webhooks were either too limited or required paid plans, so we chose Firebase for real-time data and Google Sheets for short-term logs. While effective, this setup is not ideal for large-scale or long-term deployments. Also, some structural challenges, like water leakage in vertical towers, required manual fixes using funnels and glue, which may not be sustainable in large setups.

In summary, the project successfully demonstrated a working prototype that fulfilled core monitoring, control, and prediction functionalities. Despite challenges in hardware, environmental conditions, and cloud limitations, we managed to build a reliable and cost-effective solution.

Chapter 7

Conclusion

This project set out to solve the challenge of monitoring and managing hydroponic farming systems in real time with minimal human intervention. The initial problem identified in the introduction was the lack of affordable, intelligent systems that could measure water quality, automate key functions, and provide actionable insights for nutrient management in a smart hydroponic setup.

To address this, we designed a complete IoT-based hydroponic system using the ESP32-S3 DevKit, an 8-channel relay module, and various sensors, including DHT11, TDS, ultrasonic, and a 7-in-1 soil sensor. We used a 12V power supply with a buck converter to power the system and designed the structure using PVC pipes. Actuators such as nutrient and pH motors were controlled via relays, and sensor data was uploaded every 4 seconds to Google Sheets and Firebase. We also deployed a web application to allow real-time monitoring of sensor readings and actuator status.

For evaluation, we conducted a range of test cases covering all core functionalities from sensor accuracy and relay control timing to cloud sync stability and ML model prediction accuracy. The results showed that the system met the performance expectations, achieving reliable sensing, fast relay control, accurate cloud updates, and an ML prediction accuracy of nearly 90%. These results confirm that the solution effectively addresses the core problem.

In summary, this project successfully delivers a functional and affordable smart hydroponic system that automates monitoring and control while offering predictive nutrient insights, helping address real-world challenges faced in modern soilless agriculture.

Chapter 8

Future Work

While the current implementation of our smart hydroponic system successfully achieves real-time monitoring, automated control, and nutrient prediction, there are several opportunities for future enhancements to improve its scalability, accuracy, and reliability.

One key recommendation is to develop a fully climate-controlled greenhouse environment, which would protect plants from extreme external temperatures and improve plant health and yield. This would require resources such as temperature-regulated enclosures, automatic shading systems, and humidity controllers.

Additionally, the current cloud infrastructure (Firebase + Google Sheets) works well for small-scale data logging, but for long-term and large-scale use, the system should be migrated to more scalable cloud platforms like AWS IoT Core, Microsoft Azure, or Google Cloud BigQuery. This would support better data visualization, storage, and analysis but would require investment in cloud subscriptions and backend server infrastructure.

On the machine learning side, the predictive model could be further trained using larger, real-world datasets over longer periods to enhance accuracy for seasonal planning. Integrating mobile app notifications and automated alert systems would make the platform more user-friendly and proactive.

Another important area of expansion is the use of solar power to make the system energy-efficient and suitable for off-grid locations. Integrating battery management systems (BMS) and power optimization techniques would also enhance long-term stability.

Lastly, creating a modular kit for small farmers with plug-and-play sensors and mobile integration would help make this technology more accessible. This would require design refinement, component standardization, and collaboration with manufacturers or agritech startups.

In conclusion, the project has significant potential to evolve into a commercial or open-source solution, provided there is support for environmental control, cloud infrastructure upgrades, enhanced prediction models, and user-friendly interfaces.

Chapter 9

Reflections on Learning

Working on this smart hydroponic system has been a deeply enriching experience, contributing to both our technical growth and personal development. From a technical perspective, we gained hands-on experience with embedded systems, particularly the ESP32-S3, and learned how to interface multiple sensors and actuators reliably. We also developed skills in IoT programming, real-time data acquisition, cloud integration (Firebase, Google Sheets), and machine learning, which enhanced our ability to design intelligent and scalable solutions.

We explored circuit design, relay-based control systems, and power management using buck converters and battery backup, which deepened our understanding of hardware-software co-design. On the software side, building a web application dashboard strengthened our skills in front-end development, APIs, and remote monitoring systems. Testing various cloud platforms and evaluating their limitations taught us how to make informed choices based on project needs and constraints.

Beyond technical skills, this project greatly improved our team collaboration, time management, and problem-solving abilities. We faced several real-world challenges such as hardware failures, budget constraints, and environmental factors affecting plant health, which taught us how to stay adaptive and resilient. Communicating with vendors, managing timelines (especially during component delays), and working within resource limitations helped us grow in project planning and decision-making.

On a personal level, this project boosted our confidence, creativity, and curiosity to explore sustainable tech-driven solutions in agriculture. It emphasized the importance of interdisciplinary thinking, combining electronics, programming, agriculture, and data science to address a meaningful real-world problem.

However, if we could improve one area, it would be early-stage planning and risk management. We underestimated the impact of hardware delivery delays and environmental changes on plant growth. Future projects could benefit from better contingency planning, modular development, and regular milestone tracking to avoid time loss and ensure smoother execution.

Overall, this project was not only a technical accomplishment but also a transformative learning journey that prepared us to handle complex, real-world engineering challenges with confidence and purpose.

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APPENDICES

All the project relevant code, materials and their files can be accessed using the link:

https://github.com/FahimShah651/FYP-Smart-Hydroponic-IoT-ML-Driven-Sustainable-Farming